

Revisiting problem of chilled margins associated with marginal reversals in mafic–ultramafic intrusive bodies

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Abstract

Numerous observations on mafic–ultramafic layered intrusions, sills and dykes show that chilled margins always develop as an integral part of their marginal reversals and possess the following features: (a) they are commonly much more evolved or primitive than bulk intrusion compositions, (b) evolved chilled margins are composed of the low temperature cotectic assemblages of relevant magmatic systems and (c) tend to be compositionally similar in intrusions formed from different parental magmas, (d) fine-grained chilled margins are notably absent in many intrusions, with contact rocks being represented by medium- to coarse-grained cumulates. The anomalous features of chilled margins can be partly attributed to contamination, intratelluric inhomogeneity of magma, changes in composition of intruding magma, loss of magma from the chamber, supercooling, etc. A major process still remains, however, illusive, but appears to be universally operating along the cooling margins of magmatic bodies in a liquid state, being gravity-independent and temperature gradient-driven. We recognize this not yet specified process as Soret fractionation and explain the above observations in the following way. Primary chilled margins do not commonly survive because of intensive remelting by heat flux from the interior of the chamber. The subsequently formed “secondary chilled margins” represent cumulates that crystallized from liquids produced by temperature gradient-driven Soret fractionation. At high temperature gradients the process tends to produce similar cotectic liquids crystallizing gabbro (or gabbro) from all parental magmas of a given magmatic system, resulting in compositionally similar “secondary chilled margins” that are more evolved than bulk compositions. At low temperature gradients the process produces liquids that are only slightly more fractionated than the parental magma and form “secondary chilled margins” that are more primitive than bulk compositions. This interpretation suggests that, apart from the rare cases of chilled margins that survived remelting, they should not be used as monitors for parental magma compositions of intrusive bodies, even if all conventional complicating factors were not operative.

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1. Introduction

Igneous petrologists have always been interested in defining the composition of magmas parental to intru-

sive bodies. This is because knowledge of parental magma composition is fundamental for scientific investigations in almost all fields of igneous petrology, from highly detailed studies of mineral zonation to global tectonic reconstructions concerning the evolution of the Earth. Information on parental magma composition is also of paramount importance in prospecting and exploration strategies for various ore deposits associated

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with intrusive and extrusive bodies (e.g. De Waal and Gauert, 1997; Latypov, 2002). There are several different approaches for defining the parental magma composition of intrusive bodies (e.g. bulk composition, extrusive equivalents, related dykes, melt inclusions), but the most common in use is direct sampling of chilled margins (e.g.

McBirney, 1993). This is because these are widely believed to form rapidly for a magma body emplaced into relatively cold country rocks and therefore may preserve the primary, unmodified composition of the parental magma during emplacement. Igneous petrologists have long been aware, however, of various complicating factors that may minimize the reliability of chilled margins as indicators of parental magma composition. Among them are: (a) changes in magma composition during chamber filling; (b) intratelluric inhomogeneity of magma; (c) flow differentiation during filling of the chamber; (d) contamination of magma by reaction with country rocks; (e) crystal fractionation after emplacement, (f) secondary hydrothermal alterations. Despite realization that these processes are capable of causing considerable unsystematic variations in the chemical composition of chilled margins (e.g. Wager and Brown, 1968; Cox et al., 1979; Hoover, 1989; De Waal and Gauert, 1997; Latypov et al., 2001; Barmina and Ariskin, 2002; Ariskin et al., 2003), the latter are still widely and often uncritically used for various petrological reconstructions and may therefore represent a possible source for poorly justified conclusions. We have partly touched this problem in our previous publications in connection with the origin of marginal reversals (Latypov, 2003a,b). Based on new compiled and original data, we return here to this issue to highlight several features of chilled margins of mafic–ultramafic layered intrusions, sills and dykes suggesting that they are unreliable indicators of parental magma compositions. We specifically stress that, even in the absence of all the above-mentioned complicating factors, the composition of chilled margins may still be significantly different from that of the parental magma due to some universal, but currently not yet specified liquid state, gravity-independent and temperature gradient-driven process that operates along the cooling margins

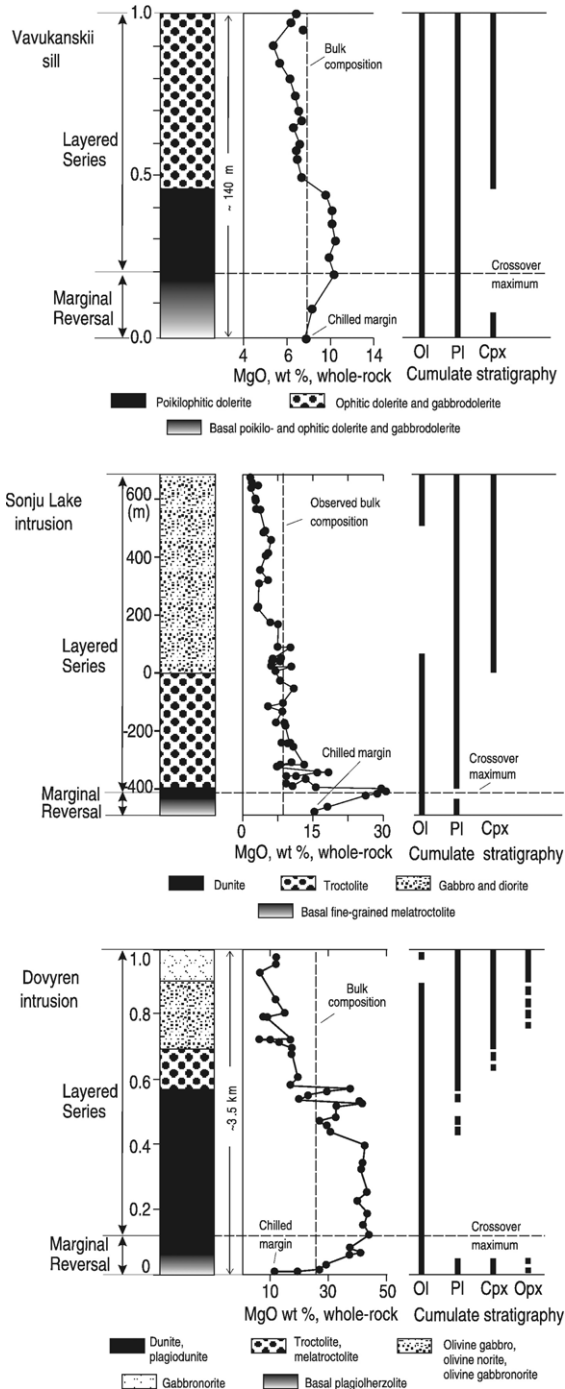


Fig. 1. Generalized stratigraphic sections through the Vavukanskii sill, Russia, the Sonju Lake intrusion, USA and the Dovyren intrusion, Russia showing variations in whole-rock MgO and cumulate stratigraphy (silicates only) with height. The intrusions comprise marginal reversals and Layered Series. The line of demarcation between these units runs through the crossover maximum exhibiting the highest MgO-content in the entire section through the intrusion. Note that the lower chilled margin can be compositionally close to (Vavukanskii sill), more primitive (Sonju Lake intrusion) or more evolved (Dovyren intrusion) than the bulk of the intrusions. Hereafter in figures and text: Pl — plagioclase, Ol — olivine, Opx — orthopyroxene, Pige — pigeonite, Cpx — clinopyroxene, Qtz — quartz, Mgt — magnetite, Z — zeolite, Acc — accessories. The thick continuous and discontinuous lines indicate cumulus and intercumulus minerals, respectively. The data is from the following sources: Vavukanskii sill; Frenkel' et al. (1988), Sonju Lake intrusion; Miller (personal communication (2005) and Miller and Ripley (1996), and Dovyren intrusion; Ariskin et al. (2003) and Kislov (1998).

of magmatic bodies and which we are inclined to interpret as Soret fractionation.

2. Universality principle as methodological basis of the investigation

An unfortunate fact of modern igneous petrology is that numerous *ad hoc* hypotheses are often proposed to explain the peculiarities of a given intrusion (or deposit), despite the recurrence of similar compositional features in many other intrusions, clearly indicating that there must be a common, fundamental geological process involved. To improve the situation we suggest following a methodological principle, which has not yet been formulated in an explicit form, despite often being used by igneous petrologists. It is a matter of common knowledge that the formation of any magmatic body is governed by a number of natural processes that are universally relevant because of their fundamental physico-chemical nature. These processes work in a similar manner in magmatic bodies, irrespective of their age (Phanerozoic, Proterozoic or Archean), geographical location (Eurasia, Africa, Antarctica, etc.), size and form (individual pillows, lava flows and lakes, dykes, sills or large intrusions), and composition of parental magmas (basaltic, rhyolitic or alkaline etc.). As a result, magmatic bodies distributed throughout the world display petrological phenomena with remarkably similar features. This permits the following inverse inference: *the widespread occurrence of a petrological phenomenon in numerous magmatic bodies implies that the process responsible for its formation is of a universal physico-chemical nature*. We refer to this as a universality principle of igneous petrology and believe that its application may help to resolve some perplexing petrological problems. Of practical importance is the consequence from this principle: *any genetic model that explains some petrological phenomenon in one specific locality but fails in others has to be questioned*. In such cases, efforts should be directed towards seeking for a general explanation that satisfies all, or at least the majority of cases. Obviously, the best way to decipher the nature of the universal phenomenon is to compile petrological information from as many field occurrences as possible. This can help to formulate the key constraints on the process required to explain the phenomenon and finally to identify the process itself. The proposed approach has its merits and demerits compared to more common practice of exploring a problem using one particular object and should be therefore used in combination with the latter. A major reason why we adopt this approach here is that it helps to avoid a danger of creating a new *ad hoc* hypothesis that may perfectly work

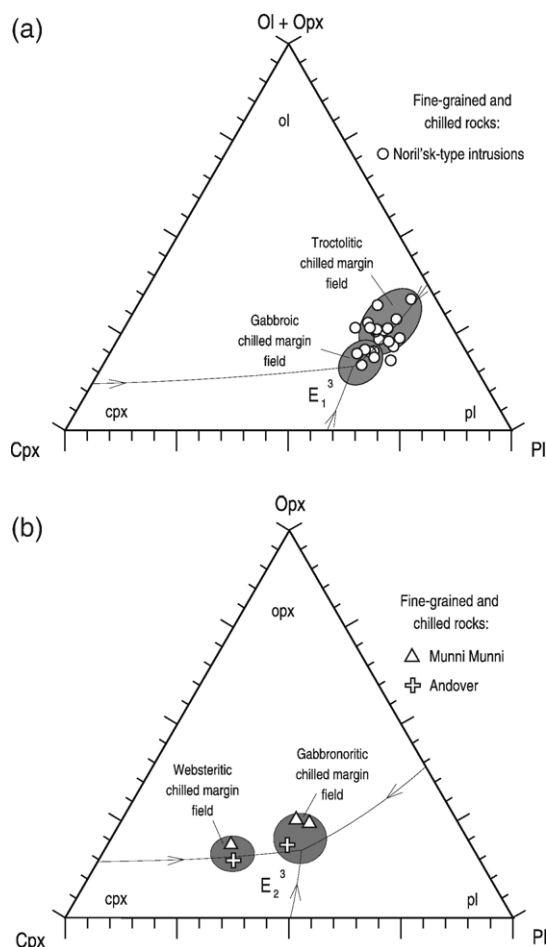


Fig. 2. Two projection planes of the isobaro-isopleth section Ol–Cpx–Pl–Qtz showing that chilled margins of the Noril'sk-type intrusions (a) and the Munni Munni and Andover intrusions (b) cover significantly different compositions for the same intrusion. The former have troctolitic and gabbroic chilled margins, while the latter two intrusions are websteritic and gabbronoritic in composition margins, while the latter are troctolitic and gabbroic in composition. Note that the chilled margin compositions of individual intrusions tend to cluster along cotectic lines, indicating phase equilibria control over their compositions. Data for the Munni Munni and Andover intrusions are from Hoatson and Sun (2002). Data for the Noril'sk-type intrusions have been compiled from many sources (Ryabov, 1992; Czamanske et al., 1995; Krivolutsкая et al., 2001). Phase relations along the projection planes are consistent with melt parameters $Mg\# = 50–75$, $An = 60–70$ and $P < 1$ kbar (slightly modified from Dubrovskii, 1998). Hereafter: cotectic and reaction lines are indicated by one and two arrows, respectively. Arrows point toward decreasing temperature. The method of plotting rock compositions on the projection planes is given in Latypov (2002). Compositions of the components are expressed in wt.%. E_1^3 — Ol + Cpx + Pl = L; E_2^3 — Opx + Cpx + Pl = L. E — eutectic point, P — peritectic point, L — melt. Superscripts indicate the number of components involved in the given equilibrium while subscripts show the number of this equilibrium in the system.

in one particular case but fail in others. Following the outlined methodology, we first review data on chilled margins from a large number of mafic–ultramafic sills and layered intrusions to reveal their characteristic features and show that their recurrence in association with marginal reversals in many intrusive bodies is indicative of some fundamental geological process involved. Strict constraints on this fundamental process are then inferred from the summarized data and used for testing the

available models for origin of marginal reversals in the hope to identify the universal physico-chemical process responsible for anomalous features of chilled margins.

3. Factual observations

We define five distinctive features of chilled margins in mafic–ultramafic intrusions that impose strict constraints on any model for their formation. These are

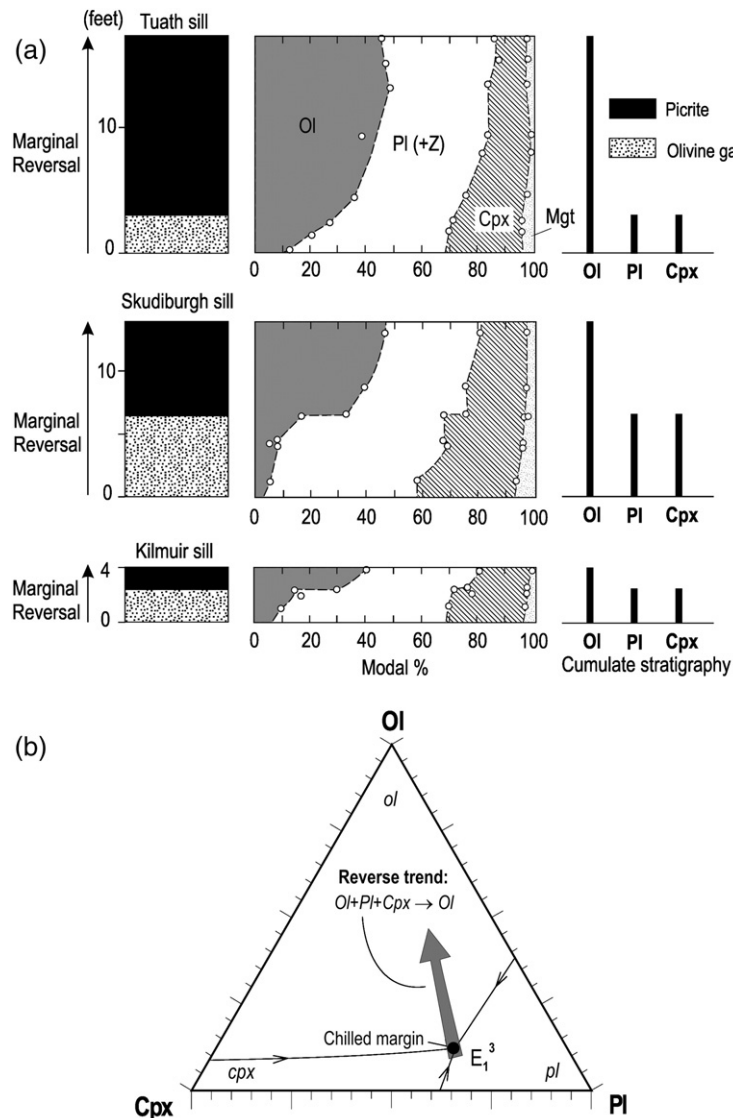


Fig. 3. Modal variations and cumulate stratigraphy of marginal reversals in north Skye sills (a) illustrating a tendency for marginal olivine gabbro to lie near the most evolved eutectic point E_1^3 ($Ol + Cpx + Pl = L$) in the magmatic system $Ol + Cpx + Pl$ (b). Cumulus mineral sequence is consistent with a reverse fractionation trend $Ol + Pl + Cpx \rightarrow Ol$. The thick continuous lines indicate cumulus minerals. The data is from Simkin (1967). The phase diagram is from Dubrovskii (1998).

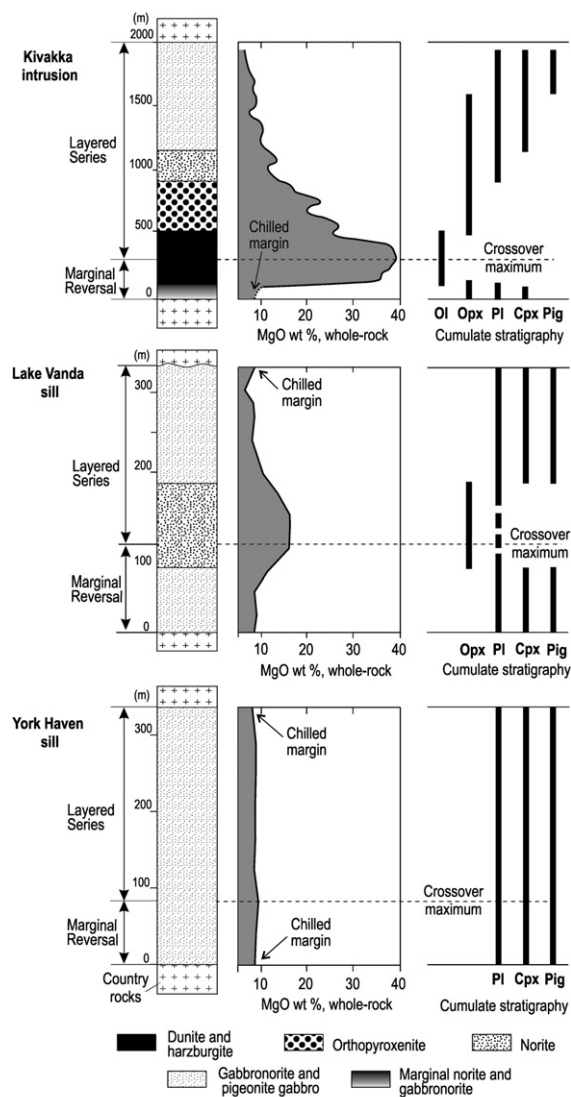


Fig. 4. Three mafic intrusions with notably different bulk compositions that evolve along the same liquid line of descent; Kivakka intrusion: $Ol \rightarrow Ol + Opx \rightarrow Opx \rightarrow Opx + Pl \rightarrow Opx + Pl + Cpx \rightarrow Pig + Pl + Cpx$; Lake Vanda sill: $Opx + Pl \rightarrow Opx + Pl + Cpx \rightarrow Pig + Pl + Cpx$; York Haven sill: $Pig + Pl + Cpx$ (see also Fig. 5). It is important that, despite being so compositionally different, the intrusions display chilled margins with similar phase (Pl, Cpx, Opx (or Pig)) and chemical (MgO) compositions. Each intrusion comprises a marginal reversal and a Layered Series. The line of demarcation between these units runs through the crossover maximum exhibiting the most primitive rock composition in the entire sections through the intrusion. The thick continuous and discontinuous lines indicate cumulus and intercumulus minerals, respectively. Data is from the following sources; Kivakka intrusion: Koptev-Dvornikov et al., 2001; Lake Vanda sill: Gunn (1966); York Haven sill: Mangan et al. (1993).

(1) the paucity of fine-grained chilled margins; (2) a lack of mass balance between chilled margin and the bulk of the intrusion, with the former being either more evolved

or, rarely, more primitive than the latter; (3) the occurrence of compositionally different chilled margins in the same intrusion; (4) a tendency for evolved chilled margins to have compositions close to low temperature cotectics in the relevant magmatic system; (5) the compositional similarity of evolved chilled margins of intrusions with different parental magma compositions. It should be noted that typically marginal zones of intrusions are texturally and compositionally heterogeneous. A question arises therefore as to what part of that heterogeneity should be qualified as a “chilled margin”? In this study, we consistently recognize a “chilled margin” as an intrusive rock closest to contact with country rocks. Another important issue concerns estimation of bulk composition of intrusions. Bulk summation of cumulates requires deep insight into mass fractions and average compositions of rocks that is difficult to obtain even for such a simple, well-exposed and well-studied intrusion as the Skaergaard intrusion, Greenland (Nielsen, 2004). Fortunately, uncertainties in defining bulk composition have little effect on our principle conclusions because the differences between bulk composition and chilled margins are commonly very significant (up to 20–25 wt.% MgO). For this reason, we usually apply bulk composition of intrusions either estimated by bulk summation of cumulates in individual cross-sections or, when it is not available, we use the observed bulk composition of individual sections that can be obtained graphically directly from the figures. Finally, the status of minerals (cumulus/intercumulus) in rocks composing marginal reversals was defined from their mode and normative composition that were compared against cotectic composition of these rocks expected from relevant phase diagrams.

3.1. Paucity of fine-grained primary chilled margins

The initial response of magma emplaced against cold surrounding rock is to form a fine-grained chilled margin. It is generally accepted that, upon further solidification, the grain size of the chilled margin increases away from intrusive contact. Since an initial chill always forms, it should be expected that every intrusion must have fine-grained marginal rocks. This is, however, far from being always the case (e.g. Huppert and Sparks, 1989). Many large mafic–ultramafic intrusions, such as the Stillwater Complex, the Rum Complex, the Black Cullins of Skye, and numerous others referenced by Wager and Brown (1968), do not preserve a fine-grained marginal chill. For example, in the Bushveld Complex the grain size, texture and chemical composition of marginal norites in the Eastern limb indicate that they are not chilled liquids but

rather represent cumulates (Cawthorn et al., 1981). In addition, in the Northern limb of the complex the contact rocks that constitute the sulphide and PGE-bearing Platreef are extremely coarse-grained melanorites and pyroxenites (White, 1994). Many mafic layered intrusions of the Fennoscandian Shield also display marginal rocks with no evidence of chilling. For instance, in the Kemi intrusion, basal contact rocks are very poorly developed. In one place there is only a 10 cm thick ultramafic marginal rock, highly enriched in chromite (up to 15 vol.%) in contact with basement granitoid. Texturally, mineralogically and compositionally it represents a cumulate rather than a chilled liquid (Alapieti et al., 1989). In the Suhanko–Konttijärvi intrusion, chilled rocks are commonly totally absent, and marginal medium- to coarse-grained gabbro-norites simply grade into footwall granitoids with an increase in partly melted siliceous fragments approaching the contact (Alapieti and Lahtinen, 2002). No fine-grained chilled margin has been detected in contact with the footwall rocks in the Narkaus intrusion, where marginal rocks are composed of medium- to coarse-grained pyroxenites and gabbro-norites. Similarly, in the Koillismaa intrusion chilled margins are not encountered anywhere at the contact with the basement, although possible remnants of them are found in the form of mafic autoliths further away from the contact (Alapieti and Lahtinen, 2002).

It should be noted in this context that the fine-grained texture of marginal rocks does not itself indicate that we are really dealing with primary chilled margins. For instance, in the Great Dyke the marginal fine-grained pyroxenites exhibit clear alignment of prismatic orthopyroxene crystals perpendicular to the margin (Wilson and Prendergust, 2001) suggesting a cumulate nature for these rocks. Similarly, in the Sonju Lake intrusion, Minnesota, marginal melatroctolites in sharp contact with country rocks compositionally correspond to a primitive adcumulate, in spite of their fine-grained texture (Miller and Ripley, 1996). It follows from the above examples that fine-grained primary chilled margins are not commonly preserved in mafic–ultramafic intrusions. One possible exception is primary chilled margin of the Bjerkreim–Sokndal layered intrusion, Norway (Duchesne et al., 1974; Vander Auwera and Longhi, 1994; Robins et al., 1997).

3.2. Lack of mass balance between chilled margins and bulk of intrusions

It is widely accepted that chilled margins form rapidly for a magma body emplaced into relatively cold country rocks and are therefore close to the parental magma

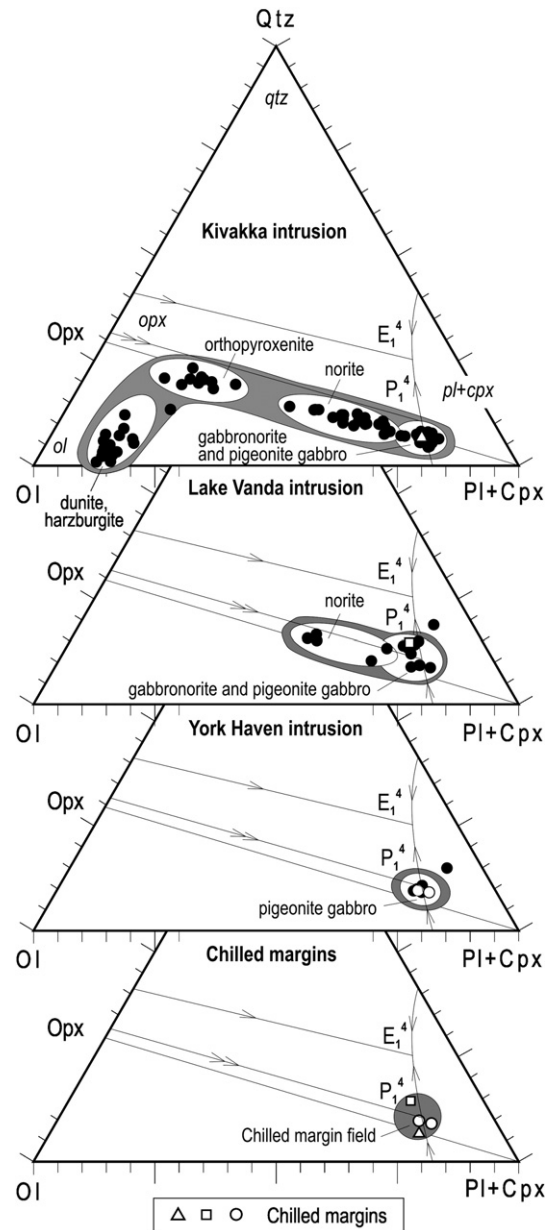


Fig. 5. A series of Ol–Qtz–(Pl+Cpx) phase diagrams illustrating that chilled margins of the Kivakka, Lake Vanda and York Haven intrusions are compositionally similar despite significant differences in their trends of crystallization: Kivakka intrusion: dunite + harzburgite → orthopyroxenite → norite → gabbro-norite + pigeonite gabbro; Lake Vanda sill: norite → gabbro-norite + pigeonite gabbro; York Haven sill: pigeonite gabbro. Note that the chilled margins (the lowermost diagram) tend to cluster around a point P indicating broadly similar gabbro-noritic compositions. Data sources as in Fig. 4. Chilled margin composition for the Kivakka intrusion is based on the modal composition of marginal rocks by Lavrov (1979). E_1^4 — Qtz + Pl + Opx + Cpx = L, P_1^4 — Opx + Pl + Cpx = Ol + L. Phase diagram is from Dubrovskii (1998).

composition (Gray and Crain, 1969; Fujii, 1974; Frenkel et al., 1988; Marsh, 1988; Tait and Jaupart, 1996, etc.). In fact, however, natural examples exhibiting similarity between the composition of chilled margin and the bulk of the intrusion, which is equated with its parental magma, are rather rare. One example is the Vavukanskii mafic sill,

Siberia, in which the lower chilled margin is broadly similar to the bulk composition of the sill (Fig. 1). Most of the data on sills and layered intrusions indicate that the composition of their chilled margins is far from the bulk composition of the intrusion (Latypov, 2003a,b). There are two possible extreme cases here. The chilled margins may occasionally be more primitive than the bulk of intrusion as is the case with the Sonju Lake intrusion, USA (Fig. 1). Much more commonly, however, the chilled margins are significantly more evolved than the bulk of the intrusion, as is observed, for instance, in the Dovyren layered intrusion, Siberia, Russia (Fig. 1). Among other examples, Simkin (1967) presented detailed vertical variations in modal olivine content through the sills of the Isle of Skye, Scotland, which clearly indicate that their bulk compositions contain 2.5–6 times the amount of olivine in and near the chilled margin. Froelich and Gottfried (1988), in particular, emphasized that none of the high TiO_2 diabase sheets in the Culpeper basin, USA, exhibited mass balance between the bulk of the intrusions and the chilled margins in any given section across the exposed tilted sheets or through those penetrated by drill cores. Similar discrepancies between the composition of the bulk intrusion and the chilled margin have been reported by Hamilton (1965) and Gunn (1966) for many tholeiitic sills and sheets in Antarctica. The rather evolved composition of the basal contact gabbrodolerite, which is not correlated with the average composition of the intrusions, has been a long-standing problem for all the ore-bearing intrusions in the Noril'sk region, Russia (Ryabov, 1992; Zen'ko and Czamanske, 1994; Czamanske et al., 1994, 1995). The same discrepancy holds for most basic-ultrabasic layered intrusions, although this is commonly overlooked due to the absence of either chilled margins or complete rock sequences or both. Some other examples of intrusions with the same lack of compositional balance have been summarized by Latypov (2003a,b). It should be emphasized here that regardless of whether

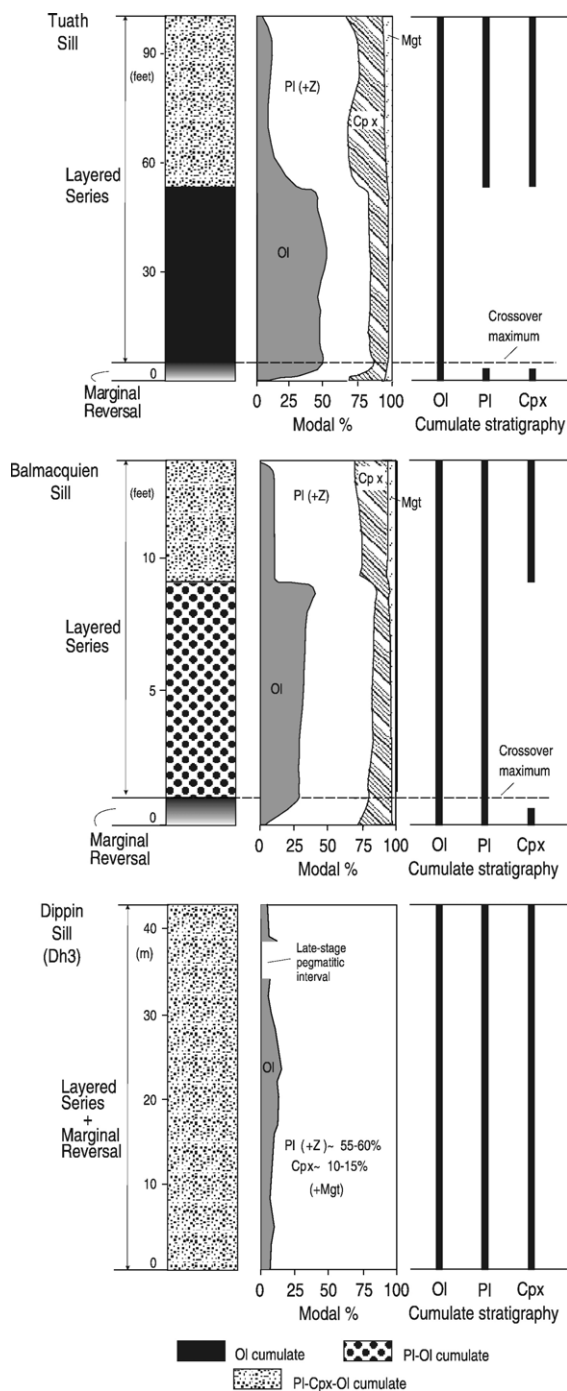


Fig. 6. Three mafic intrusions with notably different bulk compositions that evolve along the same liquid line of descent; Tuath sill: $\text{Ol} \rightarrow \text{Ol} + \text{Pl}(\pm) \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$; Balmacquen sill: $\text{Ol} + \text{Pl} \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$; Dippin sill: $\text{Ol} + \text{Pl} + \text{Cpx}$. It is important that, despite being so compositionally different, the intrusions display chilled margins with similar phase ($\text{Ol} + \text{Pl} + \text{Cpx}$) and modal (10–15%, Ol; 10–30%, Cpx; 50–60%, Pl) compositions. Each intrusion comprises a marginal reversal and a Layered Series. The line of demarcation between the units in the Tuath and Balmacquen sills runs through the crossover maxima. In the Dippin sill, it is not possible to make such a division with the available data. Data is from the following sources: Tuath and Balmacquen sills: Simkin (1967); Dippin sill: Gibb and Henderson (1978, 1992). The amount of olivine shown in the uppermost and lower rocks in the Dippin sill is based on normative compositions. The thick continuous lines indicate cumulus minerals.

chilled margins are similar to (Fig. 1, Vavukanskii sill), more primitive (Fig. 1, Sonju Lake intrusion), or more evolved (Fig. 1, Dovgyren intrusion) than the bulk of the intrusion they always represent an integral part of a basal compositional reversal.

3.3. Occurrence of compositionally different chilled margins in the same intrusion

It is well documented that intrusions can possess chilled margins with distinctly different compositions. Examples include chilled margins of the Noril'sk-type intrusions (Fig. 2a) and Munni Munni and Andover intrusions (Fig. 2b). Such compositional variation of chilled margins is commonly attributed to some complicating factor, such as local contamination or secondary hydrothermal alteration. This is difficult to reconcile, however, with the fact that the compositions of chilled margins are commonly controlled by phase equilibria. The Noril'sk-type intrusions (Fig. 2a) have chilled margins that are grouped along a cotectic line (Ol+Pl+L) in a direction approaching the eutectic point E_1^3 (Ol+Pl+Cpx=L). In a similar way, both the Munni Munni and Andover intrusions (Fig. 2b) display websteritic and gabbro-noritic chilled margins that are clustered along a cotectic line (Opx+Cpx+L) approaching the eutectic point E_2^3 (Opx+Cpx+Pl=L). It should be emphasized that in doing so, the most evolved chilled margins tend to be consistent with the low temperature eutectic assemblage of the given magmatic system, such as olivine gabbro (Fig. 2a) or gabbro-norite (Fig. 2b). This tendency is discussed in more detail in the following section.

3.4. Tendency for evolved chilled margins to have low temperature eutectic (cotectic) composition in relevant magmatic systems

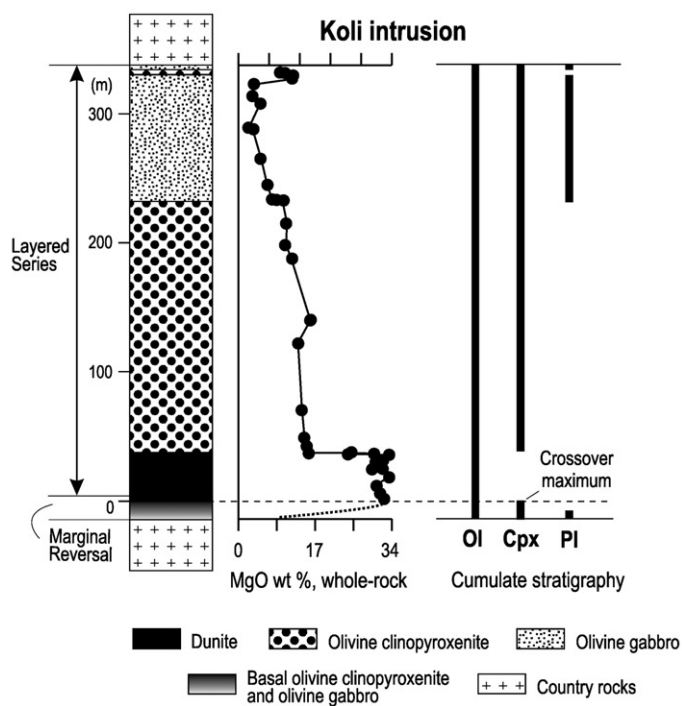
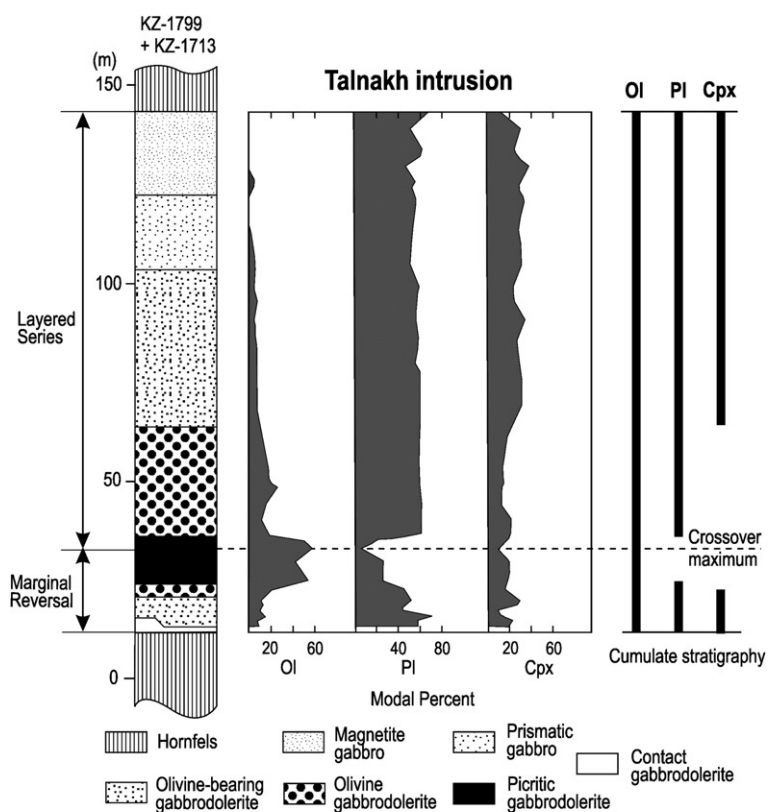
Simkin (1967) presented extensive data on the modal composition of rocks in the marginal reversals of opx-free mafic intrusions on the Isle of Skye, Scotland (Fig. 3a). These data show that the lowermost rock in the marginal reversals is an olivine gabbro with a modal mineralogy (5–12%, Ol; 25–35%, Cpx; 55–65%, Pl) that is very close to the mineral proportions expected from liquids crystallizing at the Ol–Cpx–Pl eutectic (Fig. 3b). It is important to note that the Skudiburgh and Kilmuir sills show prominent, step-like increases in olivine abundance from olivine gabbro to picrite that mirror a sudden decrease in olivine content from picrite to olivine gabbro in the overlying Layered Series (Simkin, 1967; Fig. 6). These abrupt changes in the proportion of modal olivine are the apparent conse-

quence of the low olivine content at a eutectic point E_1^3 (~5–15%, Ol) that results in a sudden rise or drop during reverse (Ol+Pl+Cpx→Ol) and normal (Ol→Ol+Pl+Cpx) fractionation trends in the marginal reversals and Layered Series, respectively (Latypov, 2003a,b). A similar cotectic assemblage (5–15%, Ol; 15–30%, Cpx; 60–70%, Pl; +recrystallized glass) that is consistent with mineral proportions expected from liquids crystallizing in the Ol+Cpx+Pl eutectic is characteristic of contact gabbrodolerites in the marginal reversals of Noril'sk-type intrusions (Czamanske et al., 1994; Turovtsev et al., 2000; Krivolutskaia et al., 2001).

A similar tendency for evolved chilled margins to approach low temperature cotectics is characteristic of orthopyroxene-bearing mafic intrusions. For instance, pigeonite gabbro and gabbro-norite, that dominate the lowermost parts of marginal reversals in Antarctic mafic sills (Gunn, 1966), display compositions (~20–25%, Opx or Pig; ~20–25%, Cpx; ~50–60%, Pl) that are consistent with mineral proportions crystallizing along the Opx(Pig)+Cpx+Pl+L cotectic (e.g. Morse, 1980). A clear compositional trend from olivine-dominant varieties towards olivine-free gabbro-norites with a roughly cotectic composition at the contact is documented in the marginal reversal of the Insizwa intrusion, South Africa (Lightfoot and Naldrett, 1984). Finally, and perhaps in the most spectacular fashion, the tendency for chilled margins to approach the composition of the most evolved rocks in the intrusion is evident in the Dovgyren layered intrusion in which the MgO-content (and modal mineralogy) of the lowermost rocks of marginal reversal closely approach that of gabbro-norite in the Layered Series (Fig. 1). Overall, the available data suggest that the formation of chilled margins in marginal reversals commonly occurs from liquids of evolved, near-eutectic or cotectic compositions. As a result of this tendency, chilled margins in orthopyroxene-free intrusions (Ol–Cpx–Pl magmatic system) are usually composed of olivine gabbro whereas in opx-bearing intrusions (Ol–Opx–Cpx–Pl magmatic system) they are composed of gabbro-norite. The distribution of mineral phases in chilled margins, as well as in marginal reversals as a whole, seems therefore to be primarily controlled by liquidus phase equilibria.

3.5. Compositional similarity of evolved chilled margins of intrusions with different parental magma compositions

This key feature of chilled margins will be illustrated using examples of intrusions that are subdivided for convenience into three groups.



3.5.1. Intrusions with different bulk compositions that evolve along the same liquid line of descent

We consider here two examples comprising three opx-bearing (Figs. 4 and 5) and opx-free intrusions (Fig. 6), respectively. The orthopyroxene-bearing intrusions (Kivakka, Lake Vanda and York Haven) have distinctly different bulk compositions, as indicated by MgO variations and different crystallization sequences; Kivakka intrusion: $\text{Ol} \rightarrow \text{Ol} + \text{Opx} \rightarrow \text{Opx} \rightarrow \text{Opx} + \text{Pl} \rightarrow \text{Opx} + \text{Pl} + \text{Cpx} \rightarrow \text{Pl} + \text{Pl} + \text{Cpx}$; Lake Vanda sill: $\text{Opx} + \text{Pl} \rightarrow \text{Opx} + \text{Pl} + \text{Cpx} \rightarrow \text{Pl} + \text{Pl} + \text{Cpx}$; York Haven sill: $\text{Pl} + \text{Pl} + \text{Cpx}$. This results in notably different rock sequences in the Layered Series of the intrusions as is evident in stratigraphic sections (Fig. 4) and phase diagrams (Fig. 5); Kivakka intrusion: *dunite + harzburgite* $\rightarrow$ *orthopyroxenite* $\rightarrow$ *norite* $\rightarrow$ *gabbro* *norite* + *pigeonite gabbro*; Lake Vanda sill: *norite* $\rightarrow$ *gabbro* *norite* + *pigeonite gabbro*; York Haven sill: *pigeonite gabbro*. It is noteworthy that the trends of crystallization and rock sequences suggest that the intrusions can be viewed as representing different parts of the the same liquid line of descent. The Kivakka intrusion covers the entire liquid line of descent, the Lake Vanda sill represents its low temperature part, and the York Haven sill the final peritectic point. (Note, that hereinafter, shown on phase diagrams are solid rather than liquid evolution paths since we plot cumulates, not liquids. It is still useful, however, because of giving indirect information about a trend of liquid evolution. As shown below, for instance, such solid paths clearly illustrate a principle difference between liquid evolution paths of the Koli and Talnakh sills). Despite the conspicuous compositional differences between the intrusions, their chilled margins are all composed of gabbro (norites (pigeonite gabbros) with remarkably similar composition, both in terms of mineralogy and Mg-content (Fig. 4). This is also evident in the clustering of the chilled margins around a gabbro (noritic point (P_1^1) on a $\text{Ol}-\text{Qtz}-(\text{Pl} + \text{Cpx})$ phase diagram (Fig. 5). It should be emphasized that the chilled margin in each of the above intrusions represents an integral part of a marginal reversal (Fig. 4).

Three orthopyroxene-free intrusions (Tuath, Balmacqui and Dippin) also have distinctly different bulk compositions, as indicated by their modal variations and different trends of crystallization; Tuath sill: $\text{Ol} \rightarrow \text{Ol} +$

$\text{Pl}(?) \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$; Balmacqui sill: $\text{Ol} + \text{Pl} \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$; Dippin sill: $\text{Ol} + \text{Pl} + \text{Cpx}$ (Fig. 6). The crystallization trends and rock sequences again indicate that these intrusions can be regarded as representing different parts of the same liquid line of descent. The Tuath sill covers the entire liquid line of descent, the Balmacqui sill represents its low temperature part and the Dippin sill the final eutectic point of this line. The most important observation here is that, despite the notable compositional difference between the intrusions, their chilled margins are all composed of olivine gabbro with remarkably similar modal composition (10–15% Ol; 10–30% Cpx; 50–60% Pl) that are consistent with phase proportions in a gabbroic eutectic point of the $\text{Ol}-\text{Pl}-\text{Cpx}$ phase diagram. The absence of whole rock chemical data for the sills, unfortunately, prohibits us showing this on a phase diagram. It should be noted, however, that the chilled margins again represent an integral part of marginal reversals in these intrusions (Fig. 6).

3.5.2. Intrusions with different bulk compositions that evolve along different liquid lines of descent

Two orthopyroxene-free intrusions (Talnakh and Koli, Fig. 7) exhibit different rock sequences resulting from their evolution along different liquid lines of descent. The Layered Series of the Talnakh intrusion follows a trend Ol (pictitic gabbrodolerite) $\rightarrow \text{Ol} + \text{Pl}$ (olivine gabbrodolerite) $\rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$ (olivine gabbrodolerite and magnetite and prismatic gabbro) whereas that of the Koli intrusion crystallizes along a path Ol (wehrlite) $\rightarrow \text{Ol} + \text{Cpx}$ (olivine clinopyroxenite) $\rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$ (olivine gabbro). Note that olivine is followed by plagioclase in Talnakh and by clinopyroxene in Koli. This difference in the order of phase crystallization is particularly evident from the distribution of rock fields in a phase diagram $\text{Ol}-\text{Pl}-\text{Cpx}$ (Fig. 8) where they define two distinct paths. What is most important here is that the evolved chilled margins of these distinctly different intrusions are, again, remarkably similar and group in the vicinity of the gabbroic eutectic point E_1^3 (Fig. 8). It should be noted the chilled margins represent the lowermost part of the marginal reversals showing trends of crystallization opposite those in the Layered Series (Fig. 7).

Fig. 7. Generalized stratigraphic sections through the Talnakh intrusion, Russia and the Koli intrusion (Finland) showing variations in modal composition, whole-rock MgO and silicate cumulate stratigraphy with height. The intrusions comprise marginal reversals and Layered Series. The line of demarcation between the units runs through the crossover maximum exhibiting the most primitive rock composition in the entire section through the intrusion. The Layered Series of the Talnakh displays a trend of phase crystallization $\text{Ol} \rightarrow \text{Ol} + \text{Pl} \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$. The Layered Series of the Koli intrusion displays a trend of phase crystallization $\text{Ol} \rightarrow \text{Ol} + \text{Cpx} \rightarrow \text{Ol} + \text{Pl} + \text{Cpx}$. Both trends of crystallization in marginal reversals are opposite those in the Layered Series. The data is from the following sources: Talnakh intrusion; Czamanske et al. (1995), Koli intrusion; Vuollo and Piirainen (1992). In pyroxenite and olivine gabbro of the Koli intrusion, olivine occurs exclusively in the form of amphibole pseudomorphs. The thick continuous lines indicate cumulus minerals.

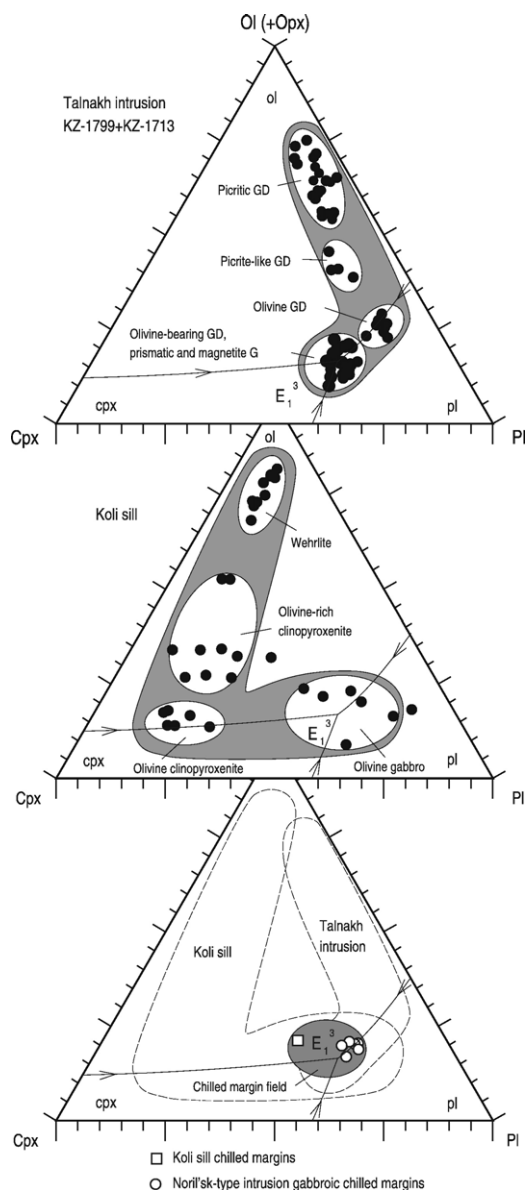
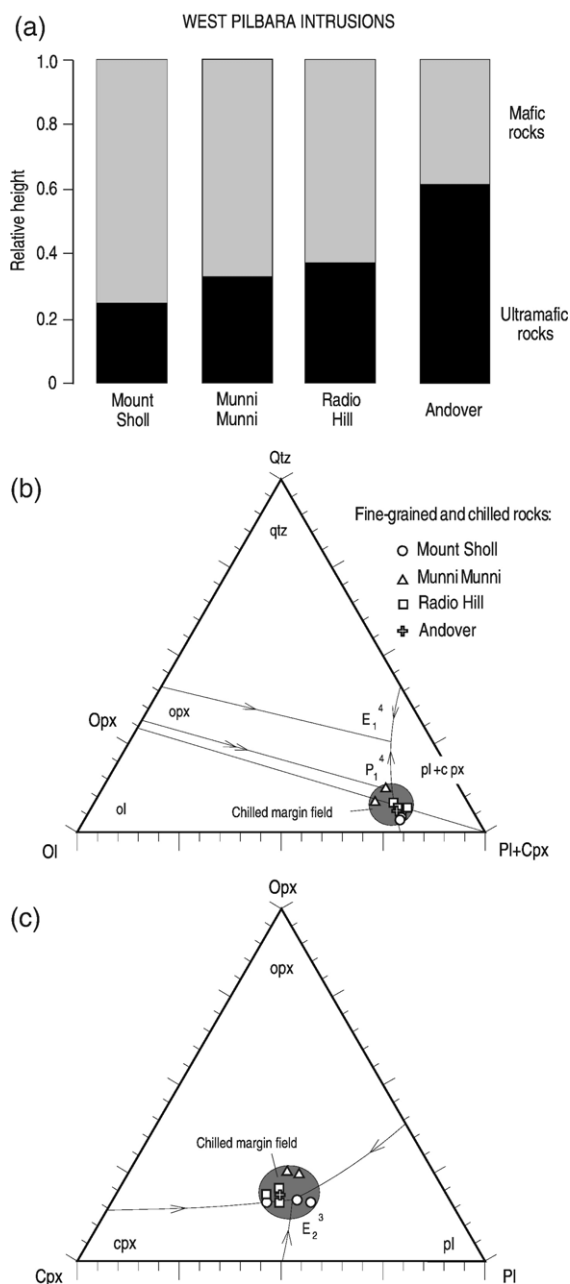


Fig. 8. A series of phase diagrams Ol(+Opx)–Pl–Cpx illustrating evolution of Talnakh and Koli intrusions along different liquid lines of descent as indicated by their rock sequences: Talnakh intrusion: pictitic GD → picrite-like GD → olivine GD → olivine-bearing GD, prismatic and magnetite gabbro; Koli sill: wehrlite → olivine-rich clinopyroxenite → olivine clinopyroxenite → olivine gabbro. Note that, despite being so compositionally different, the intrusions have compositionally similar chilled margins (olivine gabbro) as is evident from their clustering in the vicinity of the eutectic point E_1^3 (Ol+Pl+Cpx=L). Data is from the following sources: Talnakh intrusion — Czamanske et al. (1995); Ryabov (1992); Krivolutsкая et al. (2001); Koli sill — Vuollo and Piirainen (1992). GD — gabbrodolerites, G — gabbro. Phase diagram is from Dubrovskii (1998).

3.5.3. Intrusions with different bulk compositions that evolve both along the same and different liquid lines of descent

Four layered intrusions from the West Pilbara Craton, Australia (Fig. 9a), show decreasing proportions of mafic to ultramafic rocks from Mound Sholl, through Munni Munni and Radio Hill to Andover. The first three display a general trend of crystallization $Ol \rightarrow Ol + Cpx \rightarrow Cpx + Opx \rightarrow Cpx + Opx + Pl$ in which olivine is



succeeded by clinopyroxene. In contrast, the Andover intrusion follows a crystallization trend $Ol \rightarrow Ol + Opx \rightarrow Opx \rightarrow Opx + Pl \rightarrow Opx + Pl + Cpx$ in which olivine is followed by orthopyroxene. Despite significant differences in bulk composition and liquid lines of descent, the chilled margins are all composed of compositionally similar gabbronorites. This is illustrated by the clustering of chilled rocks around a gabbronoritic eutectic point E_2^3 (Fig. 9b, c).

4. Discussion

Numerous examples of mafic–ultramafic bodies presented above clearly suggest that chilled margins of any composition represent an integral part of marginal reversals. This is perhaps the most fundamental feature of chilled margins. It is therefore logical to suggest that the key to chilled margins is the process responsible for the origin of the marginal reversals. In general, a problem of marginal reversals with anomalous chilled margins can be treated in two completely different ways. One way is to consider them as representing similar, but genetically different phenomena that were produced by essentially different physicochemical processes. From this standpoint, the most appropriate explanation for any particular marginal reversal with anomalous chilled margin can be found among about 10 conventional processes, such as contamination, supercooling, multiple injection, compositional stratification of magma in the chamber, crystal settling, flow differentiation, trapped liquid shift, etc. In principle, any single or even few cases of marginal reversals with anomalous chilled margins can be successfully explained by one or a combination of several mentioned processes. For instance, magma supercooling seems to be a very reasonable explanation for marginal reversal of the Sonju Lake intrusion (Fig. 1) (Miller and Ripley, 1996). Contamination by country rocks may have played an important role in formation of marginal reversal

in the Duluth Complex (e.g. Tyson and Chang, 1984; Severson and Hauck, 1990). Successive emplacement of magma that becomes increasingly more primitive with time may well explain marginal reversal of the Kiglapait and some others intrusions (Morse, 1979, 1981; written communication, 2005). Crystal settling of intratelluric phenocrysts or newly grown crystals in the chamber can be regarded as possible interpretation for marginal reversals in the Vavukanskii sill (Fig. 1) and Dovyren layered intrusion (Fig. 1) (Ariskin et al., 2003). Marginal reversal in the Insizwa intrusion may be produced by intrusion of successively more primitive batches of magma carrying progressively more olivine phenocrysts (Lightfoot and Naldrett, 1984). Flow differentiation during intrusion of olivine or orthopyroxene phenocryst-laden magma may principally account for marginal reversals in the Shiant Isles sill (Gibbs and Henderson, 2005) and the York Haven diabase sheet (Mangan et al., 1993), respectively. Crystallization from compositionally stratified magma in the chamber adequately explains the marginal reversal in the Fongen–Hyllingen intrusion (Wilson and Engell-Sørensen, 1986). Reaction of cumulus minerals with an intercumulus melt increasing in amount towards the base seems to be a good explanation for marginal reversal in the Stillwater Complex (Raedeke and McCallum, 1984). Shrinkage-induced redistribution of intercumulus melt from the cumulate pile towards intrusive contacts may explain marginal reversals in several Siberian mafic–ultramafic intrusions (Cherepanov et al., 1982, 1983).

Such a large diversity of opinions with respect to origin of marginal reversals likely reflects a simple fact that we are commonly concerned about finding a suitable explanation for some specific case of marginal reversal. In doing so, we are seldom if ever checking whether this explanation would be appropriate for marginal reversals in other intrusive bodies. A negative result of such practice is emergence of a large number of *ad hoc* hypotheses, each of which may perfectly work for one particular case of marginal reversal, but be inadequate for others. For instance, *in situ* contamination by country rocks is inconsistent with well-developed marginal reversals in the Insizwa sill (Lightfoot and Naldrett, 1984), the Noril'sk intrusions (Czamanske et al., 1994, 1995) and the Shiant Isles Main Sill (Foland et al., 2000), which lack appreciable signs of crustal contamination even in terms of various isotopic systems. Likewise, since reaction of cumulus crystals with trapped interstitial liquid is capable to change mostly cryptic composition of minerals (e.g. Mg# or An content), it is untenable for marginal reversals of Kivakka (Fig. 4) or Jimberlana (McClay and Campbell, 1976) intrusions that show prominent reverse crystallization sequences gabbronorite,

Fig. 9. Comparative thickness of mafic and ultramafic rocks in four major intrusions (a) from the West Pilbara Craton, Australia. The first three intrusions (Mount Sholl, Munni Munni, Radio Hill) evolve along the same Cpx-dominated liquid line of descent: $Ol \rightarrow Ol + Cpx \rightarrow Cpx + Opx \rightarrow Cpx + Opx + Pl$. The Andover intrusion evolves along an Opx-dominated line of descent: $Ol \rightarrow Ol + Opx \rightarrow Opx \rightarrow Opx + Pl \rightarrow Opx + Pl + Cpx$. Two projection planes (b and c) of the system $Ol-Pl-Cpx-Qtz$ illustrates the similarity of chilled margin compositions in the Mount Sholl, Munni Munni, Radio Hill and Andover intrusions, despite significant differences in bulk compositions and trends of crystallization (a). Note that chilled margins tend to cluster around the eutectic point E_2^3 ($Opx + Pl + Cpx = L$) indicating their broadly gabbronoritic composition. Data is from Hoatson and Sun (2002). E_1^1 — $Qtz + Pl + Opx + Cpx = L$, P_1^1 — $Opx + Pl + Cpx = Ol + L$. Phase diagrams are from Dubrovskii (1998).

norite, orthopyroxenite, harzburgite and dunite. In a similar way, disequilibrium crystallization owing to high degree of supercooling cannot be applied to numerous intrusive bodies where chilled margins are much more evolved than of the bulk compositions (e.g. Fig. 1, Dovgyren intrusion), because the model predicts that the both should be compositionally identical (Latypov, 2003a). Personally, we find this situation somewhat frustrating because it hampers a further progress in our understanding the phenomenon of marginal reversals and believe that time is ripe for undertaking some steps to change the situation. As a way out we suggest following an alternative way, namely looking at the problem of marginal reversal with anomalous chilled margins through the eyes of the universality principle of igneous petrology introduced above. Application of this principle indicates that recurrence of marginal reversals with anomalous chilled margins in numerous mafic–ultramafic intrusive bodies regardless of their age, geography, form, size, and bulk composition is strong evidence that they are produced by the same fundamental physicochemical process. We should therefore direct our efforts into deciphering the nature of this process in the hope that it will shed light on a problem of anomalous chilled margins. In doing so, we should be ruled by the consequence from the universality principle: any genetic model that explains some petrological phenomenon in one specific locality but fails in others has to be questioned.

In our previous publication concerning marginal reversals (Latypov, 2003a), we found that most conventional mechanisms of magma differentiations (e.g. contamination, crystal settling, multiple magma injection, flow differentiation, compositionally zoned magma, *in situ* crystallization) are inadequate to explain some of their characteristic features and should be therefore questioned as a general reason for origin of marginal reversals. There is therefore no need to reconsider them here again. However, in the course of an informal review of this paper we have realized the necessity of returning to more detailed discussion of two major groups of hypotheses, namely those involving (a) intrusions of phenocryst-rich magmas and (b) successive emplacement of magma that becomes increasingly more primitive with time.

4.1. Critical analysis of mechanisms involving intrusions of phenocryst-rich parental magmas

This is one of the most popular groups of ideas that interprets marginal reversals as mixtures of melt with intratelluric phenocrysts, mostly olivine or orthopyroxene, that gradually increase in abundance away from an intrusive contact. In this interpretation chilled margins

tend to be evolved because of crystallizing from a liquid portion of phenocryst-rich magma. An attractive feature of this idea is that it gives a simple answer to lack of mass balance between chilled margins and bulk composition. The model is difficult to accept, however, as a general explanation for origin of marginal reversals for the following three reasons.

- (a) Emplacement of phenocryst-rich magmas appears to be an adequate explanation only for relatively simple Opx-free (Ol–Pl–Cpx system, e.g. Noril'sk intrusions) or Ol-free (Opx–Cpx–Pl system, e.g. York Haven diabase sheet) intrusions in which marginal reversals can be modelled as physical mixtures of melt with variable amounts of Ol or Opx phenocrysts. The model becomes, however, untenable for intrusions with more complicated crystallization trends, such as those involving an Ol–Opx reaction pair (Ol–Opx–Cpx–Pl system, e.g. Kivakka, Jimberlana and Monchegorsk intrusions). Let us illustrate this by taking marginal reversal of the Kivakka intrusion, Russia, as an example (Fig. 10a). The marginal reversal shows a rock sequence gabbro-norite, norite, orthopyroxenite, harzburgite and dunite that is clearly indicative of a reverse fractionation trend $\text{Opx} + \text{Cpx} + \text{Pl} \rightarrow \text{Opx} + \text{Pl} \rightarrow \text{Opx} \rightarrow \text{Opx} + \text{Ol} \rightarrow \text{Ol}$. A feature of this rock sequence is that the rocks form separate fields showing no any simple linear compositional dependence. Such rock sequence is not therefore possible to model by simple two end-members mixing of gabbro-noritic melt with increasing amount of olivine phenocrysts away from the intrusive contact (Fig. 10b). A major obstacle is that norite, orthopyroxenite and harzburgite, whose compositional fields lie well outside a mixing line, connecting the composition of the gabbro-noritic liquid with the olivine apex (Fig. 10a), cannot be produced in this way. The rock types one can form from such olivine-liquid mixtures in between of gabbro-norite and dunite are olivine gabbro-norite and olivine-rich gabbro-norite, but these are absent from marginal reversal in the Kivakka intrusion.
- (b) Crystal settling is problematic for, at least, two reasons. First, there is a specific type of intrusions, such as Fongen–Hyllingen, Norway (Wilson et al., 1981; Wilson and Larsen, 1985), Bjerkreim–Sokndal, Norway (Wilson et al., 1996) and Bol'shoi Taskil, Siberia (Krivenko et al., 1980), which possess many features that cannot be explained by crystal settling models, the most

important of which being the strongly discordant relation between modal and cryptic layering (up to 20–90°). In spite of this the Fongen–Hyllingen intrusion, for instance, shows an exceptionally well developed marginal reversal (Wilson and Engell-Sørensen, 1986). Second, crystal settling is a gravity-dependent mechanism and cannot there-

fore produce marginal reversals along subvertical walls of magma chambers. There are, however, several cases in which such marginal reversals were documented along inclined to subvertical chamber margins and even feeder dykes. Among the most spectacular examples are the Jimberlana (Campbell, 1978), Muskox (Irvine and Smith,

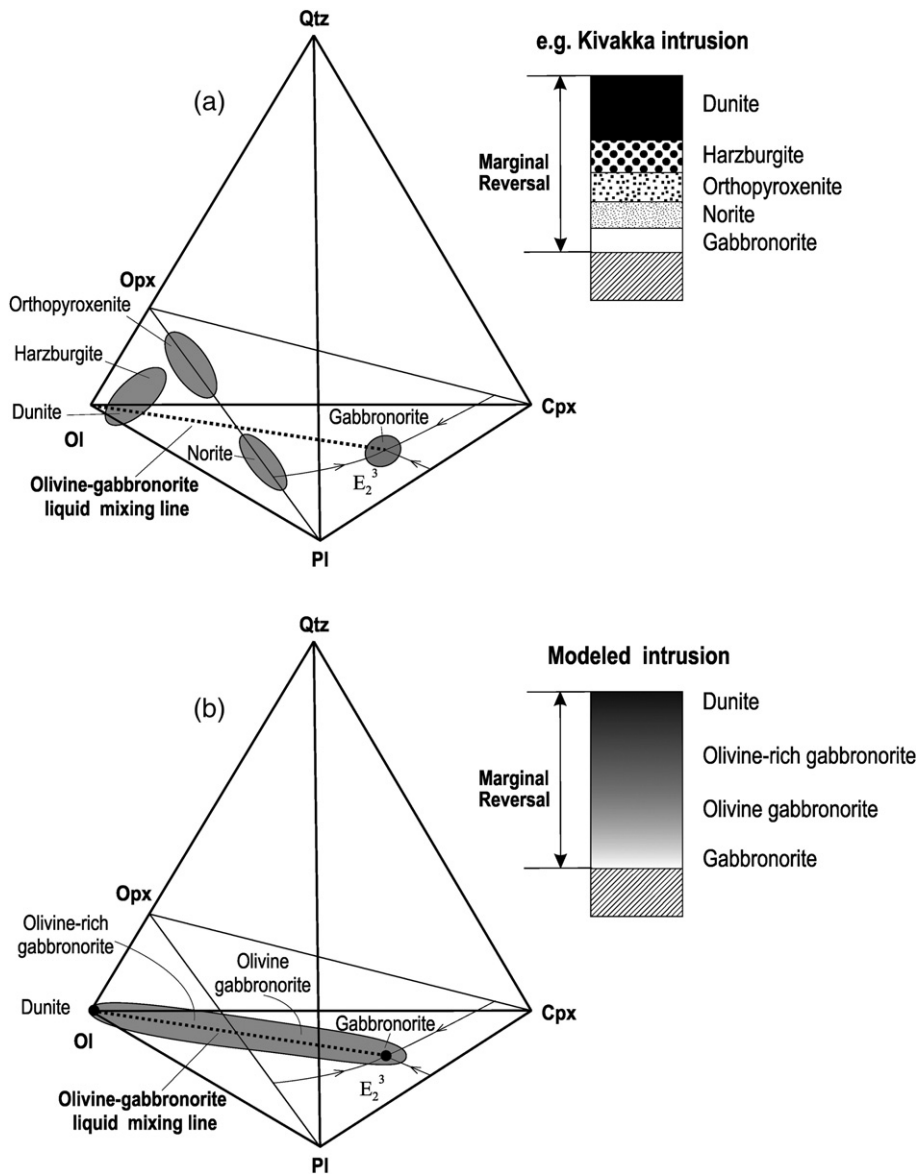


Fig. 10. A tetrahedron Ol–Cpx–Pl–Qtz in (a) shows compositional fields of rocks composing marginal reversal (gabbronorite, norite, orthopyroxenite, harzburgite and dunite) in the Kivakka intrusion, Russia (see also Fig. 11). Note that compositionally the fields are not linearly dependent. A tetrahedron Ol–Cpx–Pl–Qtz in (b) presents an attempt to model this marginal reversal by mixing gabbronoritic melt with increasing amount of olivine phenocrysts away from the intrusive contact. As a result, all rocks of the modelled reversal lie on a straight mixing line connecting the composition of the gabbronoritic liquid with the olivine apex. The reversal strongly differs from that of the Kivakka intrusion in lacking norite, orthopyroxenite and harzburgite, whose compositional fields are located well outside the mixing line (a). Instead of them, olivine gabbronorite and olivine-rich gabbronorite occur here in between of gabbronorite and dunite. E_2^3 — $Opx + Cpx + Pl = L$. See text for further discussion.

1967), Great Dyke (Wilson, 1982), and Koillismaa (Alapieti, 1982) intrusions. In particular, in the V-shaped undeformed Jimberlana layered intrusion (Campbell, 1978) the well-developed reverse fractionation sequence occurs in layers with primary dips in excess of 80°. Moreover, in the Jimberlana and Muskox intrusions marginal reversals on inclined walls are shown to have gradational transitions into subvertical feeder dykes. This is especially evident in the Jimberlana intrusion in which the two inwardly-dipping marginal successions of Pl–Cpx–Opx, Opx and Ol cumulates finally converge with the formation of a vertically zoned feeder-like dyke. The feeder dyke of the Muskox intrusion is also vertically zoned, with norite forming the margins and picrite the central part. Olivine increases in grain size, abundance, and Mg/Fe ratio from the dyke margin toward the centre while plagioclase decreases in abundance but increases in grain size and anorthite content. In this respect the mirror parts of the dyke are reminiscent of those of the marginal reversals along the inclined walls of the Muskox intrusion. These reversals typically grade inward from bronzite gabbro at the contact through picrite and feldspathic peridotite to peridotite. The gradation is essentially marked by an increase in the concentration of olivine and is accompanied by an increase in the Mg/Fe ratio of the mafic silicates (Irvine and Smith, 1967). Thus, in some respect, the vertically zoned feeder dyke of the Muskox intrusion can also be considered as being composed of two inwardly dipping marginal reversals that converge at the centre of a feeder dyke. Such feeder dykes are very important in a sense that they form a logical transition from sills and large layered intrusions with mostly subhorizontal marginal reversals towards numerous mafic–ultramafic dykes with subvertical marginal reversals (e.g. Kretz et al., 1985; Kalsbeek and Taylor, 1986; Mutanen, 1997). This indicates that both types of marginal reversals, subhorizontal in intrusions and subvertical in dykes, are essentially the same natural phenomenon and should be therefore treated in the frame of the same genetic model. It should be emphasized that dykes with such reverse D-type compositional profiles appear to dominate over those with the normal compositional trends in dyke swamps. We implemented detailed, often cm scale, geochemical sampling across about 25 mafic dykes of various thickness (from 5–10 cm

to 50 m) in the Karelia region, Russia, and the Kestiö Island, Finland, and found that all of them show the reverse compositional profiles. It is curious to note in this connection that since dykes commonly predominate over intrusions in almost any geological region, subvertical marginal reversals are actually much more widespread in nature than the subhorizontal ones.

- (c) Flow differentiation in phenocryst-rich magma, gravitational settling of phenocrysts in magma after its emplacement, and intrusion of successively more primitive pulses of magma with increasing amount of phenocrysts are not compatible with occurrences of well-developed marginal reversals in mafic sills and dykes formed from phenocryst-free parental magmas. One of such example is the Peneplain Sill, Antarctica (Fig. 11). This 330 m thick, quartz tholeiite sill that is exceedingly well exposed has been documented to have no sign of containing any phenocrysts upon formation (Marsh, 1996). The Peneplain sill has a very well-developed marginal reversal exhibiting a clear systematic progression from about 4 wt.% MgO in the chilled margin towards 7 wt.% MgO at a height of about 90 m. This maximum is followed by a slight but steady decrease in MgO throughout a central portion of the sill down to 5 wt.% at a height of about 300 m. There is clear lack of mass balance between the chilled margin of the sill (~4 wt.% MgO) and its bulk composition (~6 wt.% MgO). This indicates that marginal reversals with evolved chilled margins may form in intrusive bodies regardless of whether intratelluric phenocrysts were present or not in their parental magmas.

This is further supported by mentioned detailed geochemical sampling across several mafic dykes in Karelia region, Russia, and the Kestiö Island, Finland. Detailed discussion of results of this study is reserved for a separate paper. Here we only present a section through one 23 m thick dioritic dyke from the Karelia region, Russia (Fig. 12a). The dyke is intruded into central part of gabbro-noritic dyke and therefore not suffered from *in situ* contamination by granitic basement rocks. It is remarkably fresh and is notably lacking any intratelluric phenocrysts in the entire section of the dyke. Taken together, this indicates that the compositional profile of the dyke should be regarded as primary, not affected by contamination, secondary alteration and presence of phenocrysts. The gabbroic dyke exhibits a well-developed D-type compositional profile. From

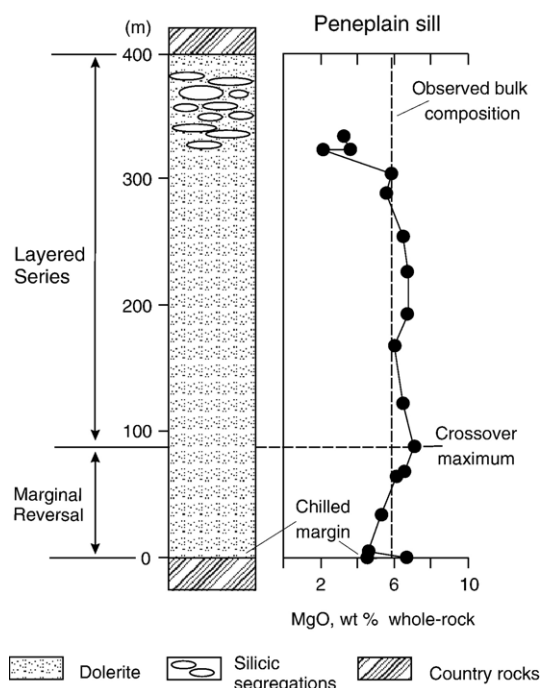


Fig. 11. Generalized stratigraphic section through the Peneplain Sill (Antarctica) showing variations in whole-rock MgO with height. Modified after Marsh (1996). The intrusion comprises a marginal reversal and a Layered Series. The line of demarcation between these units runs through the crossover maximum exhibiting the highest MgO-content in the entire section through the intrusion. The marginal reversal is characterized by an upward MgO-enrichment trend and lack of mass balance in MgO between the marginal rocks and the bulk of the intrusion. The figure aims to illustrate that marginal reversals can develop in intrusions formed from phenocryst-free parental magma. See text for further discussion.

margins inwards, it displays systematic increases in whole-rock Mg#, An(norm) and Ni content and decrease in whole-rock TiO₂ content. The changes in these parameters become especially pronounced at the margins of the body (Fig. 12b). The dyke can be regarded as consisting of two marginal reversals that converge at the middle crossover maximum with the most primitive composition of rocks. As a result, chilled margin of the dyke is characterized by the most evolved composition in the entire dyke, far more evolved than its bulk composition (Fig. 12a). Again, this is a clear indication that marginal reversals with evolved chilled margins may form in intrusive bodies produced from phenocryst-free parental magmas.

4.2. Critical analysis of mechanisms involving successive emplacement of more primitive magma

A concept of leading-edge fractionated magma implies formation of marginal reversals by successive

emplacement of magma that becomes increasingly more primitive with time (Morse, 1979, 1981). This is an old idea in petrology that is thought to make perfect sense from any point of view involving melting at the mantle source or magma staging at any intermediate level. It implies emplacement of leading pulses of evolved magma produced by three principle mechanisms: (a) fractional melting without complete mixing in the mantle source, (b) fractional crystallization of excess mafic minerals in magma flowing through the conduit, or (c) fractional crystallization and magma stratification in a subjacent chamber.

The concept is difficult to accept as a general explanation, however, because it is not compatible with one of the key features of marginal reversals. Marginal reversals occur exclusively along the cooling margins of magmatic bodies and they tend to be negligible or completely absent from the bodies intruded into warm environment, such as still hot solidifying massifs. A good example is the 660 m thick Basistoppen sill emplaced as a single pulse of magma into upper solidifying part of the Skaergaard intrusion shortly after its solidification (Naslund, 1989). Slow crystallization in warm environment resulted in one of the most extensive differentiation sequences known. The ranges of solid solutions in olivine, plagioclase, and pyroxene from the Basistoppen sill are comparable to those in the Skaergaard and Bushveld intrusions. For this study it is important to note that the sill exhibits no marginal reversal in terms of Mg# of mafic minerals and only very slight one in terms of plagioclase composition (Naslund, 1989). Another spectacular example is the 100 m thick Nadezhda gabbro-norite sill-like body in the Lakkulaisvaara layered intrusion, Russia. The body is interpreted as having formed from a portion of magma that replenished the evolving chamber and became trapped within the still hot partly consolidated cumulate pile of norite-gabbro-noritic composition (Latypov et al., in press). Detailed cm scale geochemical sampling reveals that marginal reversals at both contacts of the body are practically absent, with gabbro-norites with the highest MgO and Cr occurring at intrusive contacts and becoming progressively more evolved inwards (Latypov et al., in press). Since a temperature gradient in magma chamber is not involved in a concept of leading-edge fractionated magma, it cannot provide an easy answer as to why marginal reversals occur in magmatic bodies emplaced into exclusively cold country rocks and practically absent from the bodies intruded into warm host rocks.

Some variants of a concept of leading-edge fractionated magma account for generation of basal reversals from

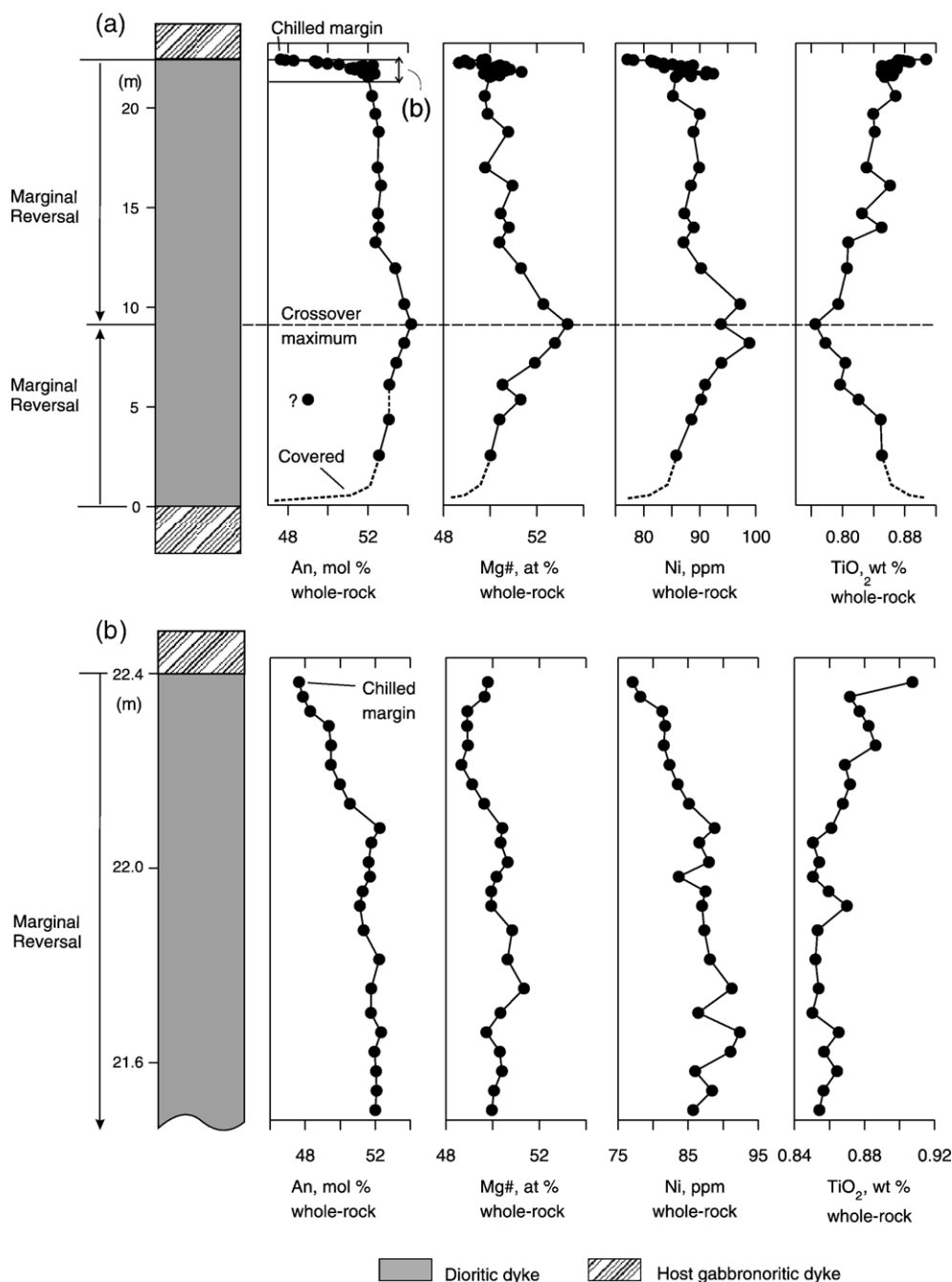


Fig. 12. Section through a dioritic dyke (a) from the Karelia region, Russia, exhibiting a well-developed D-type compositional profile. From margins inwards, there observed systematic increases in whole-rock Mg#, An(norm) and Ni content and decrease in whole-rock TiO₂ content. The changes in these parameters become especially pronounced at the margins of the body shown separately in (b). The dyke can be considered as consisting of two marginal reversals that converge at the middle crossover maximum with the most primitive composition of rocks. The dyke is fresh, uncontaminated and phenocryst-free. The figure aims to illustrate that marginal reversals with evolved chilled margins can develop in intrusions formed from phenocryst-free parental magma. See text for further discussion.

a stagnant stratified column of marginal magma that is produced by the successive influxes of denser (iron-rich), evolved magma beneath the resident, more primitive

(iron-depleted) main magma body. This implies formation of the entire marginal reversal from a restricted volume of magma in isolation from the overlying magma in the

chamber. This idea is at variance with another important feature of marginal reversals. A remarkable characteristic of some marginal reversals of layered intrusions is occurrence of sulphide mineralization extremely enriched in PGE (platinum group elements). Such marginal reversals are documented in several mafic–ultramafic layered intrusions (Koillismaa, Suhanko–Konttijärvi and Narkaus) in the Fennoscandian Shield (Alapieti, 1982; Alapieti et al., 1989; Huhtelen et al., 1989; Iljina, 1994; Alapieti and Lahtinen, 2002). One of the best examples is an exceptionally PGE-rich mineralization associated with a well-developed basal reversal (gabbro-norite, websterite, orthopyroxenite, harzburgite) in the Suhanko–Konttijärvi intrusion (Fig. 13). The PGE values attain here a grade of over 10–12 ppm, the average being of the order of 2 ppm. The most PGE-rich mineralization begins in the lower parts of the olivine cumulates and continues downwards through the pyroxenitic and gabbroic cumulates and extends into the footwall rocks. The thickness of the

marginal reversal is controlled by the floor topography of the chamber, being thickest on the gently sloping planes (up to 170 m) and thinnest on the steeply dipping slopes (about 8 m). Of importance is that the thickness of mineralization varies in concert with that of the marginal reversal suggesting that the both have been produced and controlled by the same process. Among other examples of PGE-rich sulphide mineralization in close association with marginal reversals in the Fennoscandian Shield are Fedorova Tundra intrusion, Russia (Schissel et al., 2002) and Monchegorsk intrusion, Russia (Sharkov and Smolkin, 1998; Yakovlev et al., 1999; Dedeev et al., 2002). The mineralization related to some marginal reversals attains extremely high PGE concentrations (up to 10–12 ppm; Fig. 13) indicating that sulphides could not have formed from interstitial liquid. This is because normal basaltic liquids contain negligible amounts of PGE (about 5–10 ppb) and to reach such high PGE concentrations the sulphides should come into

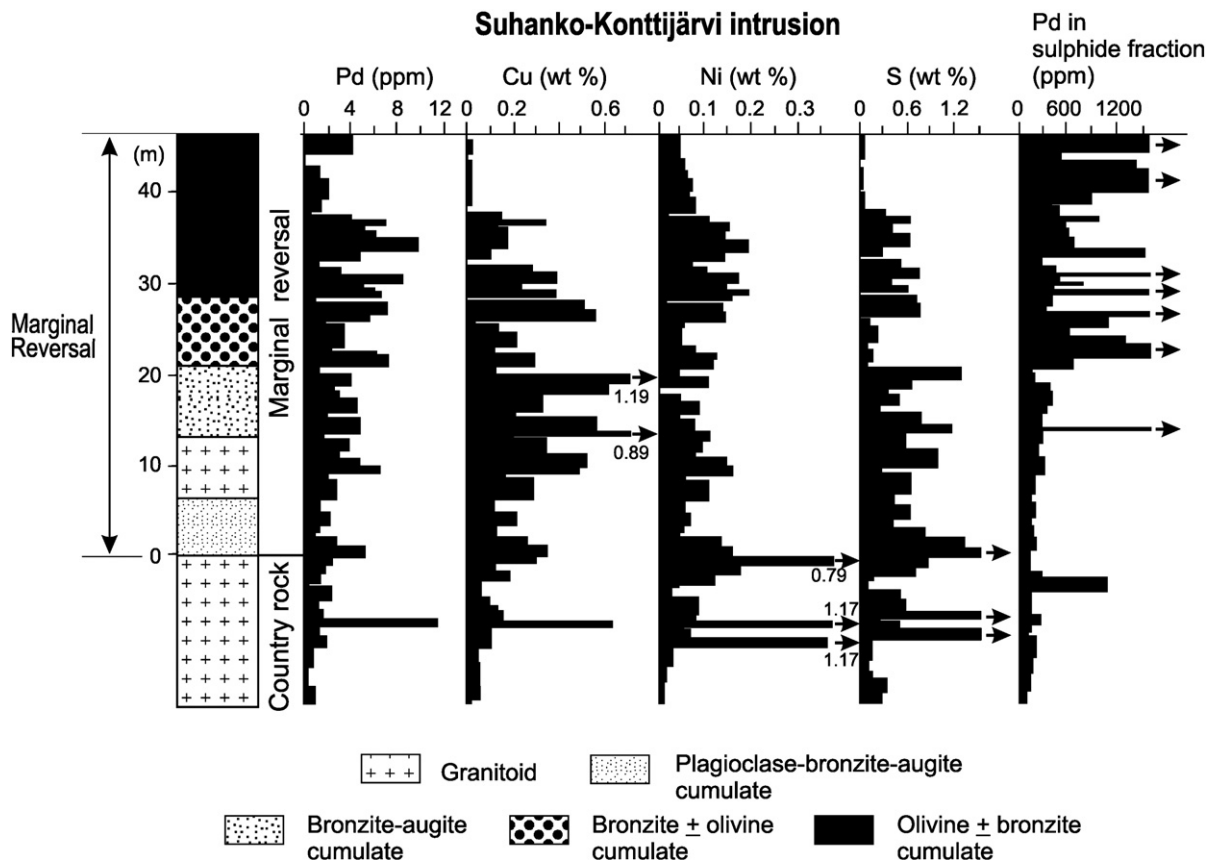


Fig. 13. Generalized stratigraphic section through a marginal reversal of the Suhanko–Konttijärvi layered intrusion, Finland, showing vertical variations in Pd, Cu, Ni, S, and Pd in sulphide fraction in mineralization. The marginal reversal is indicated by an inverse order of phase crystallization $\text{Opx} + \text{Pl} + \text{Cpx} \rightarrow \text{Opx} + \text{Pl} (?) \rightarrow \text{Opx} + \text{Cpx} \rightarrow \text{Opx} \rightarrow \text{Opx} + \text{Ol} \rightarrow \text{Ol}$. The figure aims to illustrate that sulphide mineralization with such high PGE tenor requires formation of marginal reversals in highly dynamic environment. See text for further discussion. Modified after Alapieti et al. (1989).

equilibrium with a huge amount of silicate melt, about 100,000 times of their volume (e.g. [Campbell et al., 1983](#)). An implication is that such marginal reversals should form in highly dynamic environment to allow sulphides scavenging PGE from large volumes of overlying silicate magma. This is therefore not consistent with the variants of a concept of leading-edge fractionated magma that imply generation of marginal reversals from a restricted volume of stagnant marginally-located magma.

There are some other objections that are specific to each variant of a concept of leading-edge fractionated magma (a, b and c, see above). For instance, the variant (a) invoking fractional melting without complete mixing in the mantle source is additionally untenable because parental magmas of most mafic dykes are too evolved to be derived directly from the mantle. These parental magmas are often of cotectic composition (gabbroic or gabbro-noritic) that may have only resulted from the prolonged crystallization of primary magma in staging chambers. The large group of subvertical marginal reversals in mafic dykes remain therefore unexplained in the frame of model involving mantle-derived magmas. In addition, a weakness of this model is that it requires a relatively direct ascent of magma to the surface to minimize possible mixing of earlier with later melts during rising through conduit systems or within the staging chambers at shallow crustal depths.

The variant (b) appealing to fractional crystallization of excess mafic minerals in magma flowing through the conduit seems unlikely for the following reason. In many layered intrusions, compositions at the base of marginal reversals are equivalent to those of the uppermost rocks of their Layered Series (0.5–3.0 km above). This tendency can be well seen on a stratigraphic section through the Dovgyren layered intrusion ([Fig. 1](#)). One of the most spectacular examples of such marginal reversals is documented in the Fongen–Hyllingen intrusion ([Wilson and Engell-Sørensen, 1986](#)). Let us examine an idea that this marginal reversal may have been formed from the leading-edge fractionated magma. The important point to start is to observe that the compositions at the base of the intrusion are equivalent to those about 2.5 km stratigraphically above ([Wilson and Engell-Sørensen, 1986](#)). Taking average accumulation rate in the range of 1 cm/year ([Morse, 1986](#)) to 10 cm/year ([Martin et al., 1987](#)), this implies that it should take a parental magma about 25 to 250 thousands years to attain such evolved composition at magmatic chamber conditions. In contrast, at rising velocities in the range of 0.5–5 m/s ([Turcotte, 1987](#)), it will take only several days or weeks for basaltic magma to arrive from the mantle towards the Earth's surface. This gives the longest period

of time that is available for magma to crystallize and fractionate against cold country rocks in conduits as it rises. Even this estimation may be still too optimistic because magma can start crystallizing only at the intermediate or final stages of its rising when it passes through relatively cold crustal rocks. Thus, even under the most favourable conditions, the Fongen–Hyllingen magma in conduit environment may have had several millions less time for crystallization than the same magma in the chamber. This is apparently not enough to generate leading-edge fractionated magma for marginal reversal observed in the Fongen–Hyllingen intrusion. The same logic is valid for any other intrusions with such fractionated marginal reversals.

The required degree of fractionation can be attained, however, in a variant (c), which implies prolonged magma fractionation in a staging chamber that, under favourable conditions, can lead to density stratification, with liquids becoming more evolved towards the top of the chamber (e.g. [Sparks and Huppert, 1984; Campbell, 1996](#)). Tapping of such a stratified chamber is thought to be responsible for successive emplacement of increasingly more primitive magma to produce marginal reversal in the overlying magma chamber. One general problem with this idea is a strong disparity between almost universal occurrence of marginal reversals in mafic–ultramafic intrusive bodies, from one side, and very specific conditions that should be met to allow magma stratification, from another side. Whether magma stratification is developed or destroyed is strongly dependent on relative buoyancy of rejected fluid, the location of crystallization and chamber geometry. Stratification may develop only if crystallization will occur along side-wall of chamber, producing light buoyant fluid that will flow up to roof as a laminar boundary layer (e.g. [Sparks and Huppert, 1984; Campbell, 1996](#)). There are plenty of other possibilities, such as crystallization on the floor with release of light fluid or crystallization on the roof with release of heavy fluid, which can lead to convective mixing and complete destruction of stratification (e.g. [Sparks and Huppert, 1984; Campbell, 1996](#)). An implication is that magma stratification appears to be too rare natural phenomenon to explain an almost universal occurrence of marginal reversals in intrusive bodies.

In conclusion it should be emphasized that the above analysis should be in no way taken as an attempt to question operation of the considered processes in crustal magmatic chambers. Most of these processes are thoroughly documented and may certainly contribute in one way or another to the final compositional structure of any marginal reversals. In this respect, for instance, contamination commonly reveals itself in large

unsystematic variations in composition of contact rocks (e.g. Uitkomst Complex, [Gauert et al., 1995](#)) and multiple magma pulses are clearly recorded in abrupt discontinuities in mineral and rock chemistry of marginal reversals (e.g. Duluth complex, [Grant and Molling, 1981](#)). Thus the analysis only aims to illustrate that these processes appear to not represent a general reason for origin of marginal reversals in magmatic bodies.

4.3. Features of unspecified process of magma differentiation

A question to ask here is: what does the failure of existing models to explain the origin of marginal reversals indicate? We tend to take this as nature's polite way of informing us that something crucially important is missing in our present understanding of processes operating in magmatic chambers. We seem to be currently overlooking some fundamental process of magma differentiation. This is a strong challenge for all of us to combine our petrological, theoretical and experimental efforts to decipher the nature of this not yet specified process. In this search, the following strict constraints on this process derived from natural observations summarized above may be of great help:

- (1) The process must be universal because it works in a similar manner in magmatic bodies, irrespective of their age (Phanerozoic, Proterozoic or Archean), geography (Eurasia, Africa, Antarctica, etc.), form (lava flows and lakes, dykes, sills or large intrusions), size (from 5–10 cm to 7–10 km), and bulk composition (andesitic, basaltic, picritic, etc.);
- (2) It must be almost gravity-independent because it is capable of producing marginal compositional reversals against subvertical walls of magma chambers (e.g. Jimberlana intrusion), their feeder dykes (e.g. Jimberlana and Muskox intrusion) and numerous mafic–ultramafic dykes with D-type compositional profiles (e.g. Karelian dyke, [Fig. 12](#));
- (3) It must be temperature gradient-driven because marginal reversals occur exclusively along the cooling margins of magmatic bodies and they are practically absent from the bodies intruded into still hot solidifying massifs (e.g. Nadezhda sill in the Lukkulaivaara intrusion and Basistoppen sill in the Skaergaard intrusion); to put this shorter: no temperature gradient — no marginal compositional reversals.
- (4) It must be able to produce marginal reversals from initially homogeneous liquid because marginal reversals can occur in intrusive bodies formed

from phenocryst-free parental magmas (e.g. Peneplain sill, [Fig. 11](#); Karelian dyke, [Fig. 12](#)). In addition, marginal reversals and their chilled margins tend to be composed of rocks with eutectic/cotectic compositions suggesting their crystallization from phase equilibria-controlled liquids rather than phenocryst-liquid mixtures. In other words, it should be a liquid state process;

- (5) It must be able to cause polarity in behaviour of magma components with respect to phase equilibria elements (eutectic points, cotectic, primary fields, etc.). This follows from a striking similarity of chilled margins in intrusions formed from parental magmas belonging to the same magmatic systems but displaying different liquid lines of descent (e.g. Talnakh and Koli sills, [Fig. 8](#); Australian intrusions, [Fig. 9](#));
- (6) It must be operative in highly dynamic environment to provide equilibration of sulphides with a large amount of silicate magma to become enriched in PGE (e.g. Suhanko–Konttijärvi intrusion, [Fig. 13](#)).

Close inspection of the above constraints give us some idea about the nature of the required process. Indeed, the only gravity-independent process capable to cause magma fractionation in a liquid state is chemical diffusion. The type of chemical diffusion operating in a temperature gradient is called thermal diffusion or Soret effect ([Shaw et al., 1976](#); [Spera, 1977](#); [Hildreth, 1977, 1979, 1981](#); [Walker and Delong, 1982](#); [Schott, 1983](#); [Leshner and Walker, 1991](#), [Sharkov and Bogatkov, 1998](#)). The thermal diffusion arises from the internal redistribution of species within a substance in response to an imposed temperature gradient. Diffusion of species up and down thermal gradients results in chemical differentiation of an originally homogeneous liquid. The thermal diffusion must be a universally operative process because there seems to be nothing more universal in petrology than development of a temperature gradient between intruded hot magma and cold country rocks. Combination of thermal diffusion in liquid boundary layers with vigorous convection in the main magma body leads to evolution of the whole magmatic system in highly dynamic environment. Soret effect in natural non-superheated liquid boundary layers developing in open system conditions is controlled by liquidus phase equilibria ([Latypov, 2003a](#)) and can therefore cause polarity in behaviour of magma components with respect to phase equilibria elements. Thus Soret fractionation seems to satisfy almost all the above constraints. One needs to

emphasize, however, that this option may only reflect our insufficient knowledge about processes operating in magmatic chambers and that, in reality, some other currently not yet specified fundamental process, with characteristics close to that of the Soret effect, is responsible for origin of marginal reversals. Soret fractionation can be therefore regarded as only one of the possible candidates for the required process. Resolving the whole issue about this unspecified fundamental process of magma differentiation requires a new series of experimental studies on liquid state fractionation in silicate melts subjected to temperature gradient at conditions close to liquidus.

For lack of viable alternatives at this stage, we take advantage of the Soret fractionation model recently developed to explain reverse crystallization sequences in marginal reversals (Latypov, 2003a). To resolve this problem it was proposed that Soret fractionation in natural liquid boundary layers, unlike all other mechanisms of magma differentiation, tends to force crystallization along reverse trends, from eutectics through cotectics towards one phase primary fields (Latypov, 2003a). In developing this idea, we further suggest here that marginal reversals can be regarded as a natural example of the phenomenon known in metallurgy as inverse segregation. Inverse segregation is the compositional inhomogeneity of metal alloy ingots and castings resulting from the migration of low melting point components towards their periphery, rather than towards their centre, as expected from phase equilibria diagrams (Vaughan, 1937; Hanson and Pell-Walpole, 1951; Flemings, 1974, 2000). An elegant explanation for inverse segregation was proposed almost a century ago by Smith (1917) who studied this phenomenon in metal alloy casting and even made an attempt to apply the main results of his work to some geological problems (Smith, 1926). Smith (1917) applied the well-known principle of Le Chatelier, indicating that “when the state of a system is changed the system alters so as to oppose a greater resistance to that change.” He pointed out that the cooling which occurs at the edges of ingots and castings tends to change the state of the system from liquid to solid. The only way in which this tendency can be opposed is for the system to change in such a way that the portion affected has a lower melting point and so remains fluid at that temperature. It is intriguing to think that the explanation of metallurgist Smith (1917) for the progressive increase in low melting point components towards the periphery of ingots and castings as a result of the reaction of the system against the cooling effect may be also valid for marginal reversals of intrusions.

5. “Secondary chilled margins” as a result of Soret fractionation

We can now try to understand why natural chilled margins show so many features that are incompatible with a conventional interpretation as their representing quenched samples of primary unmodified parental magma upon emplacement. To do this we need to start by considering the initial stage of marginal reversal formation. The key idea here is that chilled margins form as a result of heat and mass transfer from the interior of a magma chamber towards its margins that is caused by reaction of the magmatic systems against the cooling effect of country rocks in accordance with Le Chatelier’s principle.

5.1. Heat flux: remelting of primary chilled margins

The emplacement of hot parental magma into cold country rocks must lead to the immediate formation of a fine-grained chilled margin which will be close in composition to that of the initial magma. As discussed above, however, the majority of data on sills and layered intrusions indicate that rocks at their margins are commonly not chilled or fine-grained, and seldom similar to the initial magma composition. We believe that the reason for this discrepancy most likely lies in the fact that the initial chilled margin is rarely preserved. As shown by Huppert and Sparks (1989), the initial chilled margin in most igneous bodies can only survive for a few tens of seconds. As the conductive heat flux in the wall rock decreases with time and heat flux from the magma increases as the intrusion increases in thickness and thermal convection is initiated, the conductive heat flux in wall rock can eventually be exceeded by the heat flux from the magma. This eventually causes remelting, and even the complete disappearance, of the primary chilled margin. For sills with thicknesses from 10 to 1000 m, the remelting of initial roof chilled margins of a few tens of cm to a few tens of m in thickness is to be expected. Remelting of a chilled margin at the floor is considered to be less effective but can still occur as a result of magma flow into the chamber when heat is advected to both boundaries (Huppert and Sparks, 1989). The common lack of mass balance between floor chilled margins and the bulk composition of intrusions probably indicates that the marginal facies usually forms after prolonged meltback that destroys the initial chilled floor. This seems to be the simplest explanation for the first characteristic feature of natural chilled margins - the paucity of fine-grained chilled margins in mafic–ultramafic intrusions. It should be noted that such

thermal and physical erosion has been used to explain the common absence of fine-grained chilled margins in some layered intrusions (e.g. Alapieti and Lahtinen, 2002). To sum up, the generation of heat flux from the interior of a magma chamber towards its margins, resulting in remelting of initial chills, can be considered as a first (apart from formation of initial chills themselves) protective reaction of magmatic systems against the cooling effect of country rocks that allows them to remain in a liquid state.

5.2. Mass flux: formation of “secondary chilled margins”

With time thermal convection wanes, and the heat flux from the magma once again decreases to less than the conductive heat flux in the rock. At this stage a second generation of chilled margin begins to grow, which we take as the onset of marginal reversal formation involving Soret fractionation. As mentioned above, the key feature of Soret fractionation is to provide a mass flux of low melting point components from the interior of a magma chamber towards its margins. The apparent consequence of such transfer is a decrease in liquidus temperature of magma at cooling margins that delays the onset of crystallization and allows magma to remain in a liquid state. We consider that this is a second protective reaction of magmatic systems against the cooling effect of country rocks. The important consequence of this reaction is formation of “secondary chilled margins” with relatively evolved compositions. The exact composition of “secondary chilled margins” is largely dependent on the initial temperature difference, which is established across the liquid boundary layers after remelting of the “primary chilled margins” and heating of the cold country rock. The greater the temperature difference, the more evolved composition of chilled margins can be produced by Soret-induced fractionation.

The above idea and related consequences can be illustrated using phase relations in a simple system Ol–Pl–Cpx (Figs. 14–16). Let us start by considering the Soret fractionation trends of three compositionally different parental magmas X, Y and Z (Fig. 14a). These magmas occupy different positions along the same liquid line of descent: X corresponds to a gabbroic eutectic point E_1^3 (Ol+Pl+Cpx+L); Y is located on a troctolitic cotectic (Ol+Pl+L); and Z lies in the olivine primary field (Ol+L). Under a favourably high temperature difference, the basal part of liquid boundary layers of these magmas will consist of the Soret-produced melt corresponding to eutectic composition E_1^3 . Such temperature difference across a few centimetre thick liquid boundary layer at the contact of intrusions with cold

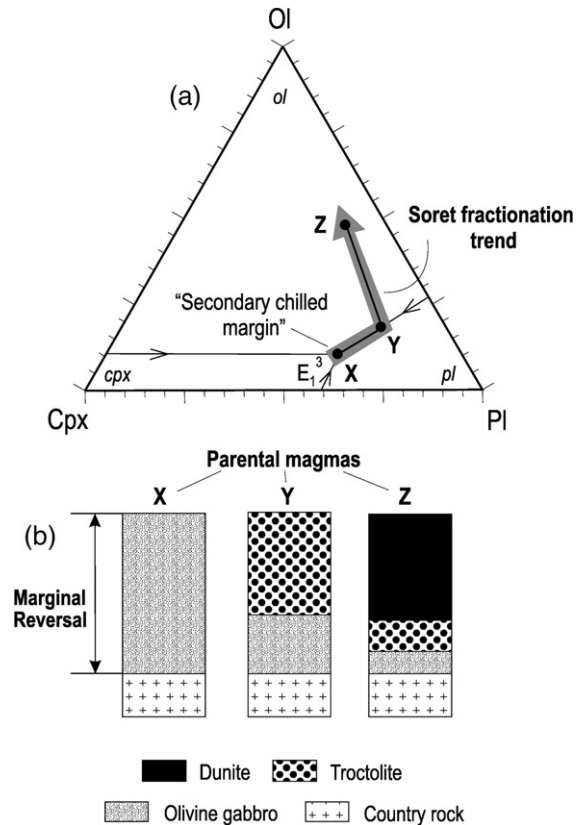


Fig. 14. Ol–Pl–Cpx phase diagram illustrating (a) how Soret-induced reverse trends produce marginal reversals with the same “chilled margin” of olivine gabbro (b) from compositionally different parental magmas Z, Y and X lying on the same liquid line of descent. Olivine gabbro crystallizes from the most evolved liquid consistent with the low temperature eutectic E_1^3 (Ol+Cpx+Pl=L). See text for further discussion.

country rocks can be as high as $>100^\circ\text{C}$ (Walker and Delong, 1982). As a result, marginal reversals of all three magmas will start with a “secondary chilled margin” of the same modal and chemical composition represented by olivine gabbro (Fig. 14b). Following this logic it is not difficult to predict that Soret-induced fractionation of parental magmas with any liquid line of descent in this system, such as A, B, C, D, E and F in Fig. 15, will result in formation of marginal reversals with essentially the same “secondary chilled margin” represented by olivine gabbro. This simple analysis provides a reasonable explanation for the next two major features of natural chilled margins. Firstly, it explains why “secondary chilled margins” tend towards low temperature cotectics in magmatic systems (Fig. 3). Secondly, it explains why the “secondary chilled margins” in intrusions with different parental magma compositions, as implied by their different mineral sequences and variable proportions of

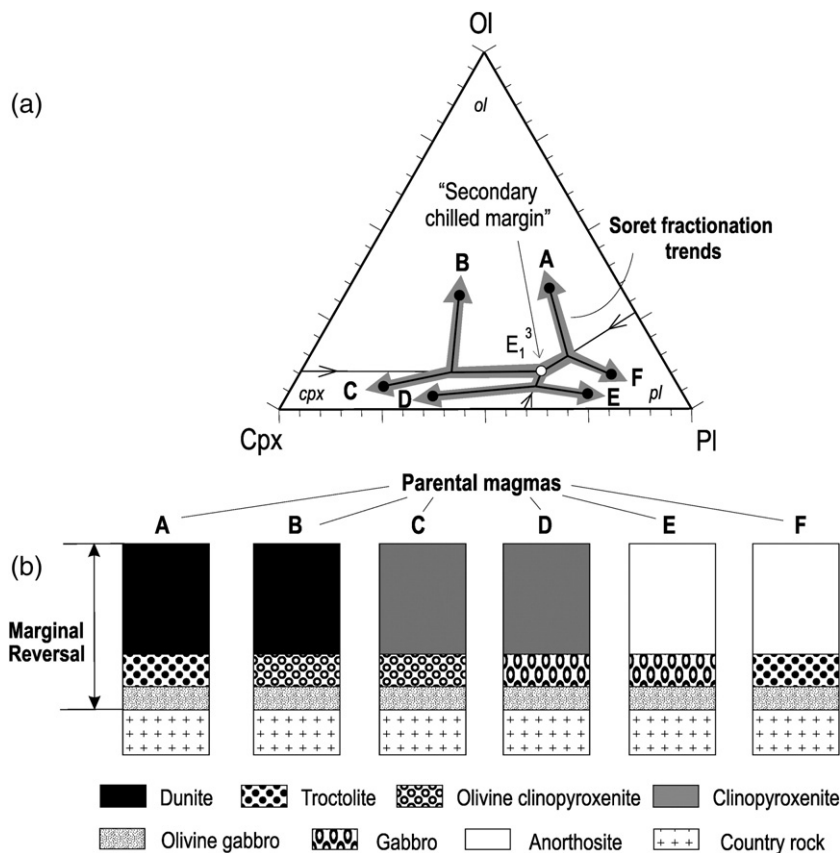


Fig. 15. A phase diagram Ol–Pl–Cpx (a) illustrating how Soret-induced reverse trends produce marginal reversals with the same “secondary chilled margin” of olivine gabbro (b) from compositionally different parental magmas A, B, C, D, E and F belonging to different liquid lines of descent. Olivine gabbro crystallizes from the most evolved liquid, consistent with the low temperature eutectic E_1^3 (Ol + Cpx + Pl = L). See text for further discussion.

mafic and ultramafic rocks, tend to be compositionally similar (Figs. 4–9).

The above analysis also clearly illustrates why the “secondary chilled margins” are commonly much more evolved than the bulk composition of intrusions (Fig. 1, Dovyren intrusion), but fails to explain why they may sometimes be more primitive than (Fig. 1, Sonju Lake intrusion) or similar to (Fig. 1 Vavukanskii sill) the bulk composition of the intrusion. To resolve the problem, let us take a closer look at Fig. 16 showing a Soret fractionation trend for the olivine-saturated magma X. So far we have been considering a situation when a temperature difference across a liquid boundary layer has been high enough to produce a eutectic liquid composition E_1^3 close to the country rock margin. This liquid crystallizes olivine gabbro that is compositionally identical to this eutectic composition and is therefore always much more evolved than the parental magma X (Fig. 16a). With a decrease in a temperature difference across a liquid boundary layer, Soret-produced liquids at the base will become more

primitive and can occupy any position on a liquid line of descent from a eutectic point E_1^3 up to the parental magma X. As a result, under moderate temperature difference, probably in the range of ~ 50 – 100 °C, the Soret-produced liquids lying on a troctolitic cotectic (Ol + Pl + L) give rise to a troctolitic “chilled margin” representing a mixture of cotectic proportions of olivine and plagioclase (point C on a tie line Ol–Pl) with variable amounts of interstitial liquids from A to B. Such troctolitic “chilled margins” may have compositions varying from eutectic E_1^3 to point C (Fig. 16a, b) and will still be more evolved than the parental magma X.

The situation may change, however, at relatively small temperature differences across a liquid boundary layer (~ 10 – 50 °C) when the “chilled margin” rocks will form from olivine-saturated liquids lying along a crystallization path from B to X. Here dunites represent mixtures of olivine with variable amounts of interstitial liquids from B to X. If the amount of interstitial liquid is dominant, the “chilled margin” compositions may lie

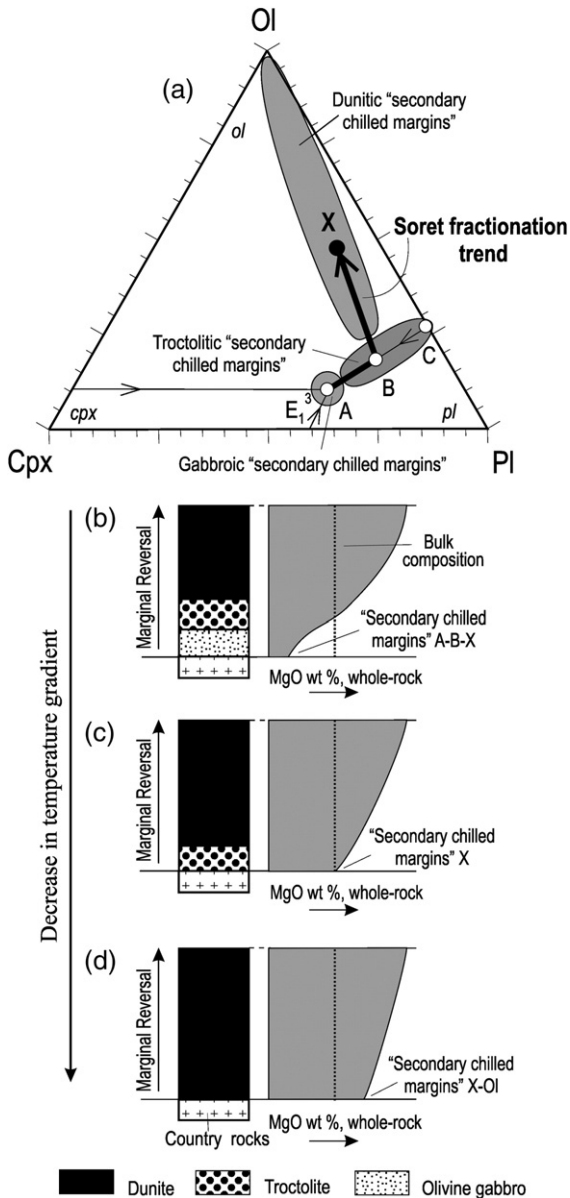


Fig. 16. A phase diagram Ol–Pl–Cpx (a) illustrating how crystallization of Soret-produced liquids from an olivine-saturated parental magma X results in marginal reversals with “secondary chilled margins” of gabbroic, troctolitic and dunitic composition. With a decrease in temperature gradient across the liquid boundary layers the “secondary chilled margins” systematically change in composition from gabbroic, troctolitic and partly dunitic cumulates (b) that are more evolved than the bulk composition towards the dunitic cumulates (d) that are, in contrast, more primitive than the bulk composition. During this process the chilled margins can accidentally achieve a composition similar to that of the parental magma X (c). E_1^3 (Ol + Cpx + Pl = L). See text for further discussion.

along a mixing line between B and X and can still be more evolved than the parental magma X. It is, however, more likely that the amount of olivine would prevail over

interstitial material so that the “chilled margin” consists of mixture between X and the olivine apex with a composition more primitive than the parental magma X (Fig. 16d). It is curious that, in this process, the “secondary chilled margins” may, accidentally, approach the composition of the parental magma X (Fig. 16c). These are not, however, “true chilled margins” but rather rocks composed of a mixture of certain proportions of olivine and interstitial material.

The above analysis thus explains the last two major features of chilled margins, namely: (a) the occurrence of compositionally different chilled margins in the same intrusion that are consistent with liquidus phase equilibria (e.g. Fig. 2) and (b) lack of mass balance between chilled margins and the bulk of intrusion, with the former being either more evolved (e.g. Fig. 1, Dovgyren intrusion) or, rarely, more primitive (e.g. Fig. 1, Sonju Lake intrusion) than the latter. It should be mentioned that the situation when “secondary chilled margins” are more primitive than the bulk composition is realized when Soret fractionation is not very effective from the very beginning of magma chamber development. This can happen, for instance, if magma is emplaced into a hot consolidating massif (e.g. Basistoppen sill into Skaergaard intrusion or Nadezhda body into Lakkulaisvaara intrusion) or into country rocks that have been preheated by high-temperature regional metamorphism or contemporaneous volcanic activity (e.g. Sonju Lake intrusion into a rift zone). Because of the minor cooling effect of the country rock, the magnitude of the thermal gradient in the boundary layer is insufficient to initiate effective operation of Soret fractionation to produce evolved chilled margins. It is important, however, that it is still high enough to produce cryptic marginal reversals by this process (Fig. 1, Sonju Lake intrusion).

6. Conclusions

Numerous examples of mafic–ultramafic intrusive bodies presented in this paper indicate that their chilled margins invariably represent an integral part of marginal reversals suggesting that the key to their origin must be the process responsible for origin of the marginal reversals. Application of the universality principle of igneous petrology to this problem indicates that recurrence of marginal reversals with anomalous chilled margins in numerous mafic–ultramafic intrusive bodies regardless of their age, geography, form, size, and bulk composition is strong evidence that they are produced by the same fundamental physicochemical process. Close examining about 10 conventional processes (contamination, supercooling, multiple injection, compositional

stratification of magma in the chamber, crystal settling, flow differentiation, trapped liquid shift, shrinkage-induced flow, etc.) illustrates that, although some specific marginal reversals can be successfully explained by one or combined operation of several processes, none of them can be recognized as a general reason for origin of marginal reversals. Failure of existing models to explain a number of characteristic features of marginal reversals appears to represent nature's polite way of informing us that our present knowledge about magma fractionation processes in crustal chambers is markedly incomplete. We seem to be unaware of some fundamental process of magma differentiation. It is necessary therefore to combine our petrological, theoretical and experimental studies to decipher the nature of this not yet specified process, which reveals itself in a spectacular form of marginal reversals with anomalous chilled margins. Constraints inferred from natural observations suggest that this must be a liquid state, gravity-independent and temperature gradient-driven process that universally operates along the cooling margins of magmatic bodies.

As one of possible variants we suggest that this unspecified process may be Soret fractionation, a non-equilibrium process operating in liquid boundary layers along the solidifying margins (Latypov, 2003a). In the frame of this concept we propose that original chilled margins that retain the parental magma composition do not commonly survive because of remelting caused by heat flux from the magma induced by flow and convection. The contact rocks that are routinely sampled by petrologists are generally "secondary chilled margins" that are formed after prolonged and complete meltback of the original chilled margins. The key role in the formation of "secondary chilled margins" is played by Soret fractionation that induces a temperature gradient-driven flux of low melting point components from the magma chamber towards its cooling contacts. As a result, chilled margins commonly tend to be consistent with low temperature cotectics in a liquid line of descent of the parental magma and are therefore much more evolved than the bulk compositions. In some cases, however, when magma is emplaced into warm country rocks, the development of a small temperature gradient results in relatively ineffective operation of Soret fractionation. The Soret-produced liquids are then just slightly more fractionated than the parental magma, so that "secondary chilled margin" cumulates formed from these liquids are more primitive than bulk compositions. The "secondary chilled margins" can be regarded as forming in response to heat (that cause remelting) and mass (that cause flux of low melting point components)

transfer from the interior of a magma chamber towards its margins that represents a reaction of magmatic systems against the cooling effect of country rocks in accordance with the well-known principle of Le Chatelier. It should be emphasized that compositional effects of Soret fractionation is almost invariably complicated by some other processes such as *in situ* contamination by country rocks, change in magma composition upon emplacement, intrusion of phenocryst-bearing magmas, etc., that may cause additional and sometimes quite essential changes in composition of chilled margins. A future task is to identify reliable criteria to safely separate compositional effects of these processes from those of the Soret fractionation itself.

The study thus suggests that Soret fractionation contributed by other complicating factors may result in formation of chilled margins that will give misleading information about parental magma composition of magmatic bodies and their use for such purposes is therefore highly undesirable. We would like to specifically emphasize that, even in the absence of all the above-mentioned complicating factors, the composition of chilled margins may still be significantly different from that of the parental magma due to inferred fundamental gravity-independent and temperature gradient-driven process, which we interpret here as Soret fractionation. It should be pointed out that this generalization is strictly valid for secondary chilled margins, since primary ones which survived remelting can still preserve reliable information about parental magma composition. Such primary chilled margins appear to be, however, very rare phenomenon even for such small intrusive bodies as dykes let alone large layered intrusions (Chistyakova et al., work in progress). Of course, a caution about use of chilled margins as indicators of parental magma composition is far from novel (e.g. Wager and Brown, 1968; Cox et al., 1979), but it is still worth reminding in the light of current wide application of chilled margins for various petrological purposes. The pertinent question to ask is: "What method should we use to define parental magma composition if chilled margins are not any more a reliable option"? Although a detailed discussion of this issue is beyond the scope of this paper, it appears that there is no universal method that can be applied to all intrusive bodies to obtain a reliable estimate of their parental magma composition. Despite its all shortcomings (e.g. incomplete section due to erosion, multiple magma pulses, intratelluric phenocrysts in parental magma) the best approach is to use the bulk intrusion composition with its imperative phase equilibria testing on correspondence of a liquid line of descent to the observed mineral crystallization sequence and mineral compositions (e.g.

Irvine, 1970; Frenkel' et al., 1988; Vander Auwera and Longhi, 1994; Latypov et al., 2001; Ariskin and Barmina, 2004).

The above explanation should be regarded as a working hypothesis that may form a starting point for those researchers who would become interested in the problem in question. We strongly encourage petrologists and experimentalists working in this field to test our hypothesis in order to speed up finding better solution for the problem of marginal reversals with anomalous chilled margins. Since our first publications on this subject (Latypov, 2003a,b) we have been criticized by some researchers on various grounds for bringing Soret fractionation back to a petrological stage. In doing so, we were not, unfortunately, suggested any viable alternative explanation, which would survive a test against constraints, inferred from natural observations on marginal reversals here and earlier (Latypov, 2003a,b). We would like to note in this connection that we fully admit that our attribution of marginal reversals to Soret fractionation may prove to be finally incorrect. It is quite conceivable that some other fundamental, but still unspecified process of magma differentiation is responsible for the marginal reversals. The strict constraints derived from natural observations on marginal reversals allow us, however, to expect that its operating characteristics will not be too far from those of the Soret effect. We would like also to point that we are looking forward to and are ready to accept any alternative idea from our colleagues that would suggest better explanation to the phenomenon of marginal reversals. Let us complete this paper with words from the recent original book by Alexander R. McBirney (2004, p. 190): “We cannot afford to reject new ideas that fail to fit our current beliefs, for as the iconoclasts like to remind us, we may be rejecting a revolutionary break-through. The history of science has many examples of how a new hypothesis, even if it proves to be faulty, stimulates thought, discussion, and new directions of research. As Hannah Arendt put it: “Better a creative error than an uncreative truth.”

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